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THESIS

A MODEL FOR THE PROPULSION FUEL
CONSUMPTION OF AN AIRCRAFT CARRIER

by

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Sources of this variability include the nonlinear transformation of operational data into fuel logistics data, the nearly deterministic engine reacting to inputs from a stochastic environment, and the effects of increased engine wear and ship's crew fatigue on engine performance. Implementations of this variation in a simulation indicate that conventional estimation techniques for fuel consumption may seriously overestimate the endurance capability of the aircraft carriers. The simulation results show that the distribution of endurance time resembles a normal distribution, with the estimated mean decreasing and estimated variance increasing as unpredictabilities in various environments are considered.

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A MODEL FOR THE PROPULSION FUEL CONSUMPTION OF AN
AIRCRAFT CARRIER

by

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Submitted in partial fulfillment of the
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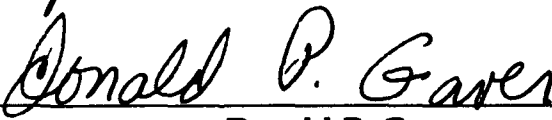MASTER OF SCIENCE IN OPERATIONS RESEARCH

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ABSTRACT

Speed and propulsion fuel consumption characteristics of United States aircraft carriers are modeled to determine how unpredictabilities in operational, engineering, and wartime environments affect the endurance capability of the ship. Research into the characteristics of steam propulsion plants on ships show that variability may exist in the amount of propulsion fuel required to support ship operation for a given period of time.

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I. THE ROLE OF PROPULSION FUEL CONSUMPTION ESTIMATES IN OPERATIONAL LOGISTICS

Above all, petrol governed every movement.

> Winston Churchill [Ref. 1:p. 284]

The war was decided by engines and octane.

> Joseph Stalin [Ref. 1:p. 68]

Our ships sailed on water, but they moved on oil, and the demand never ceased.

> Rear Admiral W.R. Carter, U.S.N. [Ref. 1:p. 186]

Operational Logistics Planning requires forecasts of propulsion fuel consumption by conventional naval aircraft carriers under a wide range of demands. The ships must maintain sufficient propulsion fuel levels to endure chaotic, wartime strike operations, as well as peaceful ocean transits. The logistician's estimate of the ship's propulsion fuel consumption rate, along with information on the fuel level of the carrier, determines the predicted endurance of the vessel. This estimate is a prediction of how long a ship will be able to perform any mission, peaceful or warlike, before requiring refueling from a Combat Logistics Force (CLF) ship.

The completion of any Naval mission requires an accurate estimation of the fuel required to maintain the needed operational tempo; the value of this estimation increases with mission duration. This thesis will describe the current methods the United States Navy employs to predict propulsion fuel

consumption, will propose improvements on those methods, and then will suggest effects of the improvements when United States Navy aircraft carriers are involved in three broad scenarios: peacetime transit, transit followed by one day of flight deck operations, and continuous flight deck operations.

A. PROBLEM STATEMENT

Logistic statistics from World War II indicate that 45.1% of the daily weight requirements per man, per day in the Pacific were Petroleum, Oil, and Lubricants (POL) [Ref. 1:p. 260]. Rear Admiral R. Kusak, Chief of Staff for the Japanese Pearl Harbor Strike Force, considered the problem of predicting fuel consumption and refueling frequency to be second only to secrecy in operational importance [Ref. 2:p. 216]. Today's naval forces are no less dependent on a large, uninterrupted supply of POL.

According to Coralski in his book *Oil and War* the United States military of the late 80's expended close to 500,000 barrels of petroleum daily, compared to 484,000 barrels used at the height of World War II [Ref. 1:p. 332]. When considering that over seven times the number of men and women served in the military during 1945 as in peacetime in 1986, one can now understand the increased reliance of the U.S. military on petroleum. On a large scale, the seeds for dilemma are sown. The inevitable surge of oil usage in war appears to be an historically established phenomena.

B. ANALYSIS PROCEDURE

A variety of methods exist to predict propulsion fuel consumption in naval ships. Each method employs a unique Measure of Effectiveness (MOE)

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to determine the productivity of a unit of fuel. Some of these MOE's are gallons/man/day, average speed, and daily operational level.

These methods assume a linear transformation of statistical operational data to fuel consumption behavior, determinism in the behavior of the ship's propulsion plant, no accelerated wear and tear on the plant or fatigue in the ship's crew. While these methods may satisfactorily predict fuel usage levels under peacetime conditions, under an increasing operational tempo they may not adequately account for fuel consumption.

To improve the accuracy of fuel consumption predictions, several factors must be analyzed. The basic nonlinearity of the fuel usage versus ship speed relationship found in fuel economy curves must be understood so that variations in operational tempo can be accounted for in planning. Note too the ship's engineering plant may consume fuel within a possible range of rates for one specific speed. The possibility of accelerated engine wear and crew fatigue under wartime conditions must be realized. While these effects have little significance while an aircraft carrier operates in peacetime, where life-threatening fuel shortages are nonexistent, they could help account for the unexpectedly high levels and unpredictabilities of fuel consumption experienced by engines in a wartime environment.

C. MODELING AND THE USE OF SIMULATION

Preliminary models are proposed for the variations in fuel consumption by aircraft carriers in Chapter IV. These represent both engineering and operational effects. Once the additional factors affecting the fuel efficiency of an aircraft carrier are modeled, they are implemented in a simulation of the time required for a CV-63 class aircraft carrier to consume one million gallons

of ship propulsion fuel, designated by the Navy as F-76. First, the estimated time to consume one million gallons (1 MGAL) of fuel is calculated using the method of an average speed per day. Next, each suggested model improvement will be implemented to test for any significant deviation from the original method.

The first improvement in the fuel estimating technique is to model the carrier operational behavior in one day with a speed distribution instead of just an average speed. Next, the variability of fuel consumption due to the deterministic engine reacting to a stochastic environment of weather, plant configuration, and human operators will be modeled by lognormal increases in the fuel levels for each sampled speed. Finally, the possible accelerated degradation of engineering plant and crew efficiency will be added to the above model enhancement by increasing the parameters of the fuel distribution over time.

D. UTILITY OF ANALYSIS

The results of the analysis and simulation correspond with empirical data on fuel consumption only when the conditions are similar to those in effect when the empirical data was gathered. These empirical data, the fuel economy curve relationship, published in the Naval Warfare Publication (NWP) 11-1, *Characteristics and Capabilities of US Navy Combatant Ships*, [Ref. 3], applies to a specific environment:

- low sea state and winds
- constant speed for several hours to allow transients in engineering plant to settle.
- no large turns or maneuvering

The results from the simulation show significant reductions in the endurance capability of one million gallons of F-76 for an aircraft carrier when the additional operational factors are added. Time-speed variation of aircraft carrier, hypothetical variance in engine efficiency, and accelerated plant degradation are far less important under routine peacetime conditions, than under the demands of intense wartime activity. Under the duress of a wartime environment they may quickly become critical. Assumptions that these factors are collectively negligible may well not hold for the complete range of aircraft carrier operations. The ship's propulsion plant is a dynamic, nonlinear system. Under low-tempo, peacetime conditions refueling will only require coordination with the battlegroup CLF assets. However, should the carrier be involved in high intensity conflict, unexpected refueling needs could endanger both the carrier and the CLF ship. Refueling at sea under unanticipated conditions significantly degrades the combat capability of the ships involved. This thesis will illustrate the possible nature of the variations and unpredictabilities involved so that they will be recognized as an important issue in operational planning.

II. PRESENT METHODS FOR FUEL ESTIMATION

A variety of methods can be used to model propulsion fuel usage. Each method uses a different MOE to determine the productivity of a unit of fuel, yet all methods apply historical data to forecast usage levels. These forecasts are presently given by a point estimate, with no additional information regarding likely variations.

A. GALLONS/MAN/DAY APPROACH

Historically based logistic planning factors are used to aid the United States Navy in the forecasting of supplies. The planning factor for POL consumption is given in gallons per man, per day. [Ref. 4]

Post-exercise and post-war experiences are frequently aggregated over several months into this gallon/man/day MOE. Though this type of information provides some rough hindsight into required logistics support, G/M/D simply does not consider the nature of the operation each "man" may have been involved in to cause fuel consumption. Fuel is consumed by engines, not men, in response to demand.

B. DAILY FUEL BASELINE

The Daily Fuel Baseline (DFB) is one type of MOE for fuel consumption used by the Atlantic Fleet for estimates of propulsion fuel consumption by class of ship [Ref.. 5:p. 2]. This MOE specifies the fuel consumption in terms of producing, by ship class, a level of operation: inport steaming, independent steaming, carrier operations, etc... Though DFB considers the major aspects of

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fuel consumption in a widely and unpredictably varying operational tempo, shortfalls in accurate estimation occur because fuel consumption depends on more than ship's speed and operation. Corrective engineering maintenance, the Preventive Maintenance System, The Heat Program, to name a few, and the command's attitude towards fuel use all contribute to variations in usage of fuel, according to USN CAPT Gary W. Zwirschitz, CINCLANTFLT Comptroller in 1986. These factors are not trivial; CAPT Zwirschitz considered them significant enough to make the following statement in his paper entitled *Atlantic Fleet Surface Force Fuel Management*:

> Based on the foregoing, it is reasonable to conclude that daily baselines, as a pure measure of how much fuel is required for an "average " day underway, are unreliable.[Ref. 5:p. 4]

C. FUEL CONSUMPTION PREDICTION BASED ON AVERAGE SPEED OF ADVANCE (SOA)

The average SOA approach to fuel consumption prediction uses a weighted average speed to summarize the variety of speeds at which an aircraft carrier travels over a period of time. This average speed is entered into the official fuel economy data for the class of ships [Ref. 3] to determine the average fuel usage figure. Thus, by predicting the average speed the aircraft carrier will maintain, the average fuel use is determined.

This current method implicitly assumes that the fuel-speed relationship is linear; only the average of the independent variable (speed), μ_S, determines the average dependent variable (fuel), μ_F:

$$\mu_F = a\mu_S + b$$

where a and b are constants.

This assumption may not be valid, particularly during high and variable speed conditions, because the fuel economy curve on any ship is nonlinear (see Figure 1); one cannot use a linear relationship if any variance occurs in the speeds used. A fuel-speed relationship for the CV-63 class aircraft carrier is exhibited in Figure 1. The square points represent data from NWP 11-1 for the CV-63 class aircraft carrier [Ref. 3: p. 2-25]. The polynomial equation at the top of the figure is a fourth order fit of the data using the software package CricketGraph for the Macintosh computer system.

$$y = 1885.89 - 285.42x + 58.04x^2 - 3.26x^3 + 0.07x^4$$
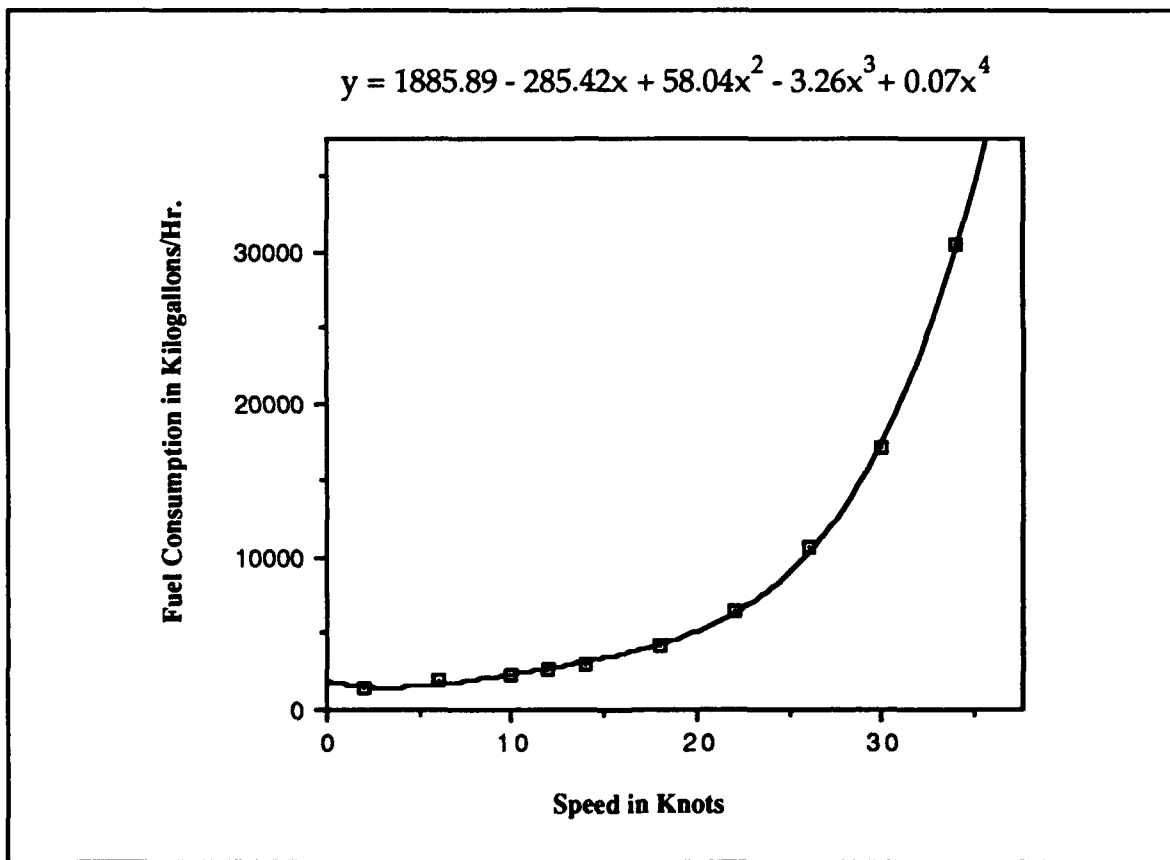
Figure 1. CV-63 Fuel Economy Curve

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The lack of linearity of the relationship between average speed and fuel consumption was observed in a 1967 study for the Chief of Naval Operations by the Center for Naval Analysis on propulsion fuel requirements. The study states that using average speed to determine average fuel is essentially incorrect; it is at best an approximation that is valid when speed variations are small. [Ref. 6: Appendix C, p. 9-10]

More recent models, such as the Battle Force Operations Replenishment Model [Ref. 7], the Replenishment At Sea Model [Ref. 8], and the Resupply Sealift Requirements Generator [Ref. 9], calculate fuel consumption using the daily SOA of the ship or group of ships as input [Ref. 10:p. 5, 19, 25]. The Replenishment At Sea Model recognizes the additional fuel use due to tactical maneuvering (i.e., zig-zag maneuvers or sprint-drift) and applies an additional constant[Ref. 10:p. 19]. While these models are adequate for ocean transits or other operations where speed variations are small, they will not hold for any operation requiring a wide range of speeds and frequent speed changes to accomplish a mission. Flight deck operations are an example of this type operation. The aircraft carrier must adjust course and speed frequently to maintain a desired wind speed and direction across the flight deck. The ship maneuvers to meet tactical requirements based on geographic position and enemy threats.

Additional error may be generated by the fuel economy curves used to determine the fuel consumption-speed data. These curves are a collection of point estimates which give a one-to-one correspondence between fuel use and speed. Models which use data from a fuel curve typically use a polynomial curve to best fit the data points, drawn from sources such as

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Naval Warfare Publication 11-1 [Ref. 3]. These publications draw their data from ship trials conducted specifically to determine fuel consumption versus speed.

The data drawn from sea trials may themselves be questionable when used for any purposes other than estimating fuel consumption under steady-state operating conditions with an efficient plant configuration under low-wind and sea-state conditions. The Naval Sea Systems Technical Manual Series (NSTM) chapter 094 specifies conduct of two trials from which fuel data might be drawn: standardization trials and fuel economy trials. [Ref. 11]

1. Standardization Trials

Standardization Trials are conducted by the ship to determine engineering relationships between speed, RPM, torque and shaft horse power of the ships at designated drafts [Ref. 2:p. A12]. These trials are typically conducted for one ship of the class shortly after commissioning; NSTM specifies the necessary conditions for these trials:

> Trials should not be conducted when weather conditions require excessive use of rudder to maintain ship on course, or when the effects of wind or sea is sufficient to materially affect the results.[Ref. 11:p. A12]

Hence, standardization trial specifications limit demands on the ship in a way that is not operationally typical. This specification makes their use in logistics questionable.

2. Fuel Economy Trials

Fuel Economy Trials are to be conducted to obtain fuel usage data for a class of ship [Ref. 2:p. B1]. However, the *Naval Ship's Technical Manual* on Ship Trials has recognized the potential shortfalls of generating logistics prediction from engineering test data:

It should be noted that such data represents performance characteristics of the ship under ideal conditions (i.e., a ship with clean underbody paint, clean propellors, undegraded machinery, and with negligible effects of wind and sea. Such fuel data do not represent the ship or her class under normal operation conditions and should not be used for logistic purposes [Ref. 11:p. B1].

D. POTENTIAL HAZARDS OF POINT ESTIMATES

All methods mentioned use a point estimate for estimated fuel use. Since the endurance of a carrier is determined by its fuel level, this estimate of fuel consumption, when only point estimates are considered, translates into ship endurance by the following equation:

$$\text{Endurance} = \frac{\text{Fuel Available}}{\text{Estimated Fuel Consumption}}$$

This endurance capability of a carrier is given as a point estimate; no potential variation of the endurance estimate exists to assist in understanding the variability of the estimate. The failure to quote variability of uncertainty measures could give decision makers a false sense of confidence in the endurance of their ships.

III. VARIANCE IN FUEL USAGE PREDICTIONS

For fuel, total consumption during an exercise may closely approximate the total for a task force of equal size in war for the same number of days. Variance will still be great, but some of the variance will be predictable.... Other variances, resulting from responses to enemy factor, are unpredictable.

Samuel D. Kleinman, Center for Naval Analyses [Ref. 12:p. 9]

The amount of fuel an aircraft carrier consumes to accomplish a specific mission may vary because of three factors: the difficulty of transforming operational requirements into logistic requirements, variance in engineering plant performance, and degradation of engineering plant and crew efficiency.

The projection of fuel consumption, together with the ship's fuel level, determines the projected endurance of that ship. If the projection of fuel consumption has variance, the perceived offensive and defensive postures of the ship must have some variance, or unpredictability. The connection of operational requirements and fuel consumption will next be explored.

A. TRANSFORMING OPERATIONAL REQUIREMENTS INTO LOGISTIC REQUIREMENTS

I was low on fuel ... if and when brought under air attack on the following day, I would have to use extra fuel in dodging and maneuvering. Therefore fuel was a very important consideration--the basic one.

Japanese Vice Admiral Kurita, CINC Imperial Japanese
Second Fleet [Ref. 1:p. 323]

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The aircraft carrier must make sufficient speed to conduct its primary mission of flight deck operations. Course and speed changes are made constantly to maintain a desired relative wind course and direction and to remain within prescribed geographic boundaries, or "box."
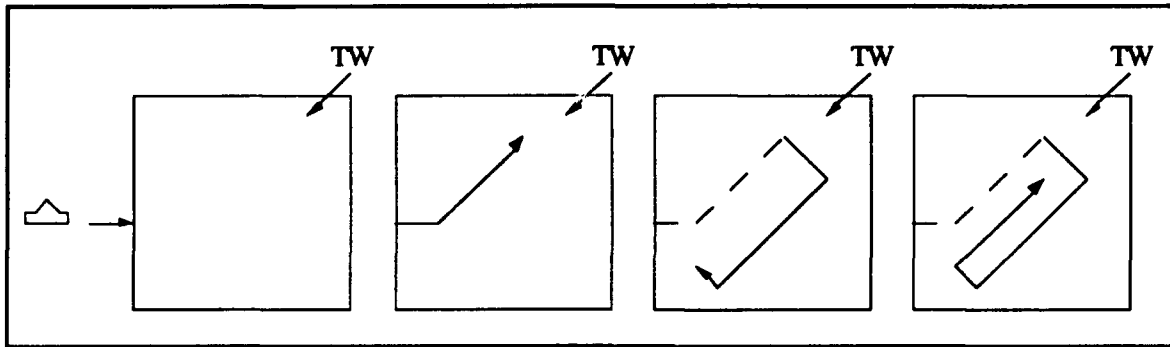
Figure 2. Sample Carrier Behavior during Flight Deck Operations

The relative wind course and direction are critical in maintaining constant flow of air across the flight deck for the launching of aircraft. Geographic boundary constraints apply when the aircraft carrier wishes to remain in the vicinity of land, or to minimize veering off from the Plan of Intended Movement (PIM). When the carrier is not engaged in flight operations, it is typically in transit, traveling at a relatively constant speed.

To predict the requirements for fuel consumption, the operational requirements for speed must be stated as precisely as possible. For peacetime transit operations, estimated fuel consumption can be drawn from fuel consumption tables or projected from present consumption levels with some reliability. Moreover, errors are not as operationally significant as those made during wartime. Such is not the case during wartime carrier flight deck operations, when the ship must react with speed to unpredictably varying

(stochastic) environmental elements, such as true wind course and speed, and to unanticipated operational requirements.

If the aircraft carrier were required to conduct this type of flight deck operation illustrated in Figure 2, for a 24 hour period, the following time-speed characteristics might, for example, be as shown in Figure 3.
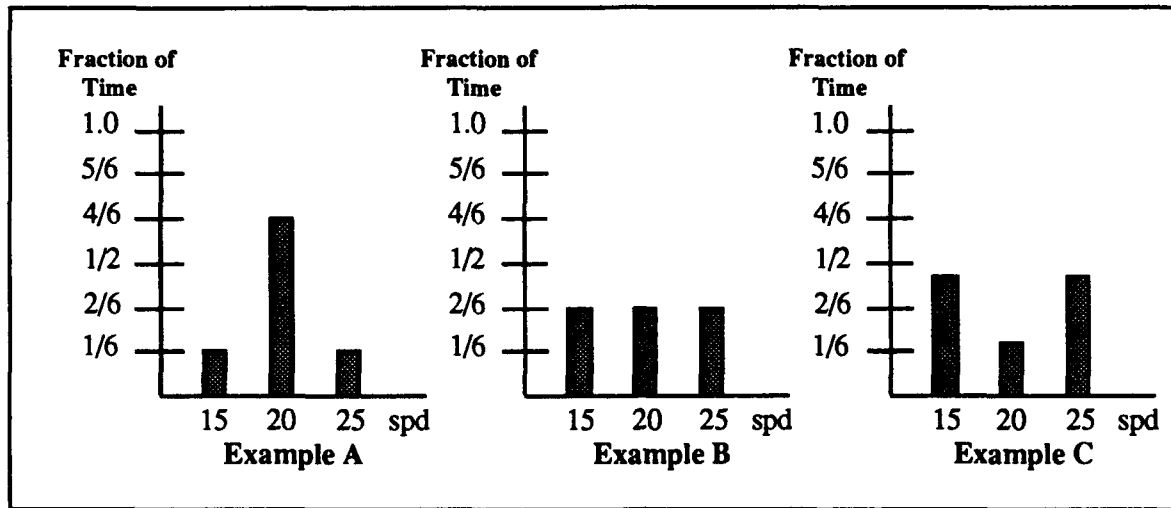
Figure 3. Carrier Time-Speed Characteristics

All of these time-speed variations over 24 hours have an average speed of 20 knots. Thus one might describe these events as "flight deck operations with an average speed of 20 knots." Attempting to predict fuel consumption solely from an average speed estimate would produce the same fuel consumption for the 24 hour period for each of the above example scenarios.

If the same time-speed characteristics were used to sample from a fourth order polynomial fit of a fuel economy curve (Figure 1), the fuel consumption characteristics would be as shown in Table 1.

TABLE 1.   SPEED AND FUEL CONSUMPTION AVERAGES AND STANDARD DEVIATIONS

	Speed Average in knots	Speed Deviation in knots	Fuel Consump. Average in gallons/hr	Fuel Consump. Deviation in gallons/hr
EXAMPLE A	20	2.89	5676	1779
EXAMPLE B	20	4.08	5968	2482
EXAMPLE C	20	4.56	6114	2755

The convexity of the fuel-speed economy curve means that simply using anticipated average speed to estimate average fuel consumption will tend to systematically underestimate average fuel consumption. Since fuel-speed economy curves appear to be convex (Figure 4) this effect is predicted by Jensen's inequality [Ref. 13: pp. 153-154].

Specifying the operational requirements for an aircraft carrier just as an average speed is a crude prediction. The possibility of a distribution of speeds about the average created by the carrier reacting to an environmental element requires that some degree of variance in the actual values must be recognized in any estimate of fuel consumption.

B. VARIATION IN ENGINEERING PLANT PERFORMANCE

Unpredictability, or variation in consumption, can easily occur, even in the deterministic system that represents a ship's engine. System input such as the command for speed may be fixed, but the remaining inputs may vary stochastically as they react to a very real, random environment of weather, machines, and people.

where

$$E[h(x)] = ah(s) + (1-a)h(t)$$

$$E[x] = as + (1 - a)t \qquad \text{and } E[h(x)] \geq h(E[x])$$
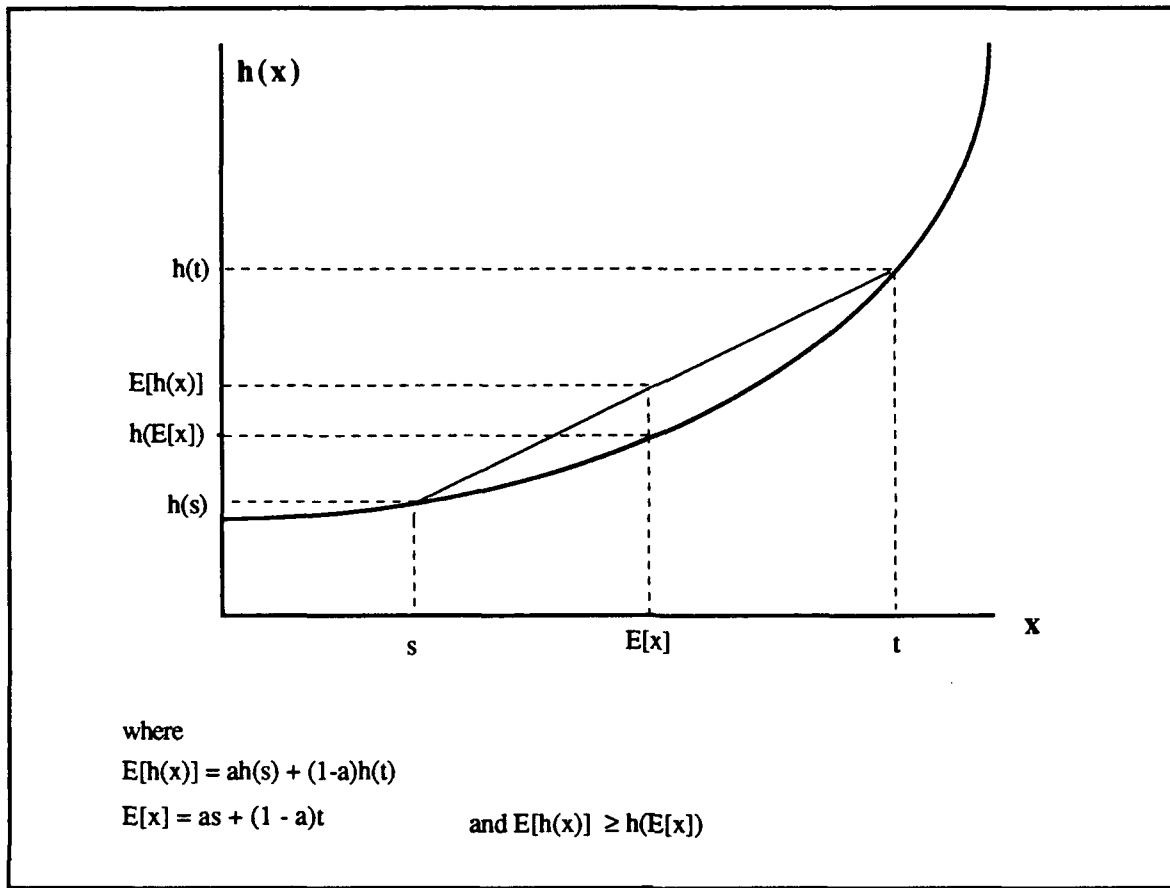
Figure 4. Monotonic Increasing Nonlinear Curve

A propulsion plant system diagram is shown in Figure 5 with the primary inputs, fuel and speed orders, and the primary output, propulsion.

There are, however, a number of additional categories of inputs to the system in addition to those mentioned above. These inputs are illustrated in Figure 6.

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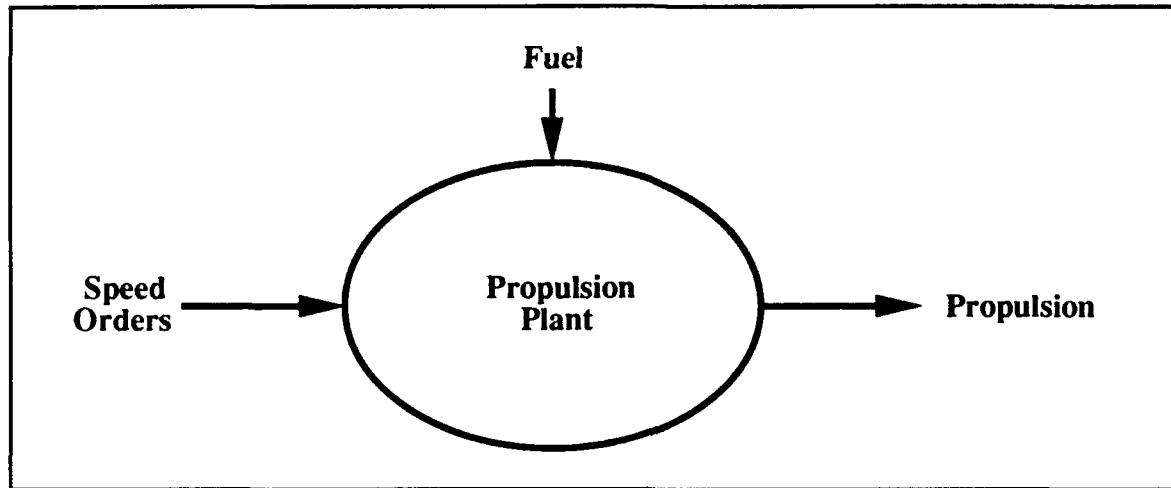
Figure 5. Theoretical Propulsion Plant System Diagram
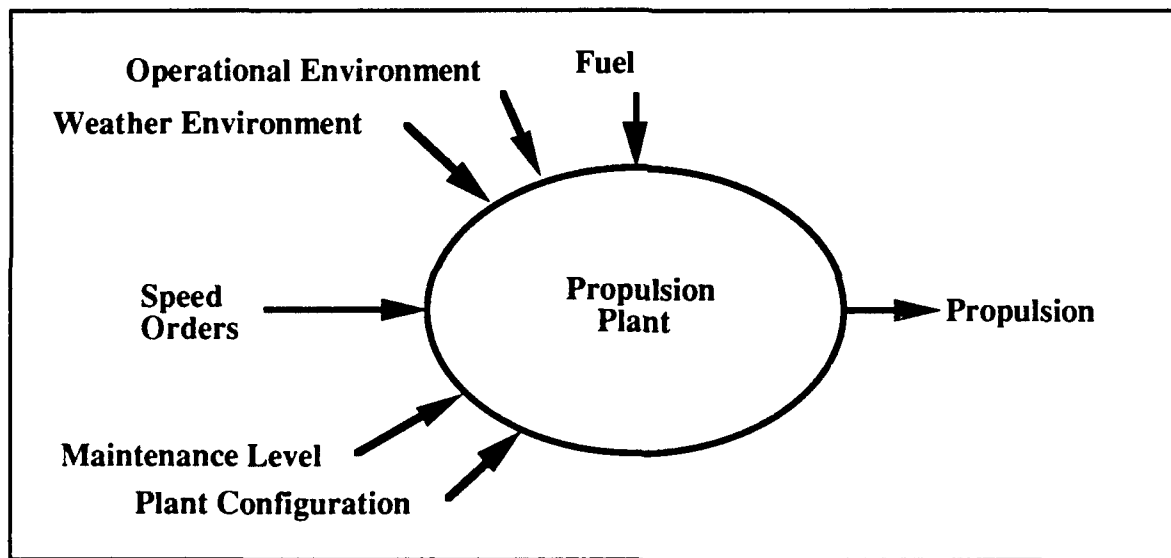
Figure 6. Comprehensive Propulsion Plant System Diagram

Ideally, propulsion plant behavior is deterministic: a unique set of inputs will produce a nearly unique output. The speed orders and amount of resulting propulsion are determined in advance, yet additional impacts on the system arise from environmental, engineering, and human events. The

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overall effect is to add a potentially large variability to energy requirements and fuel consumption..

To assist in the appreciation of the variety of inputs a ship's engineering plant receives, Table 2 lists factors which affect engineering efficiency.

TABLE 2. SOURCES OF VARIATION IN ENGINEERING PLANT PERFORMANCE

CAUSE	EFFECT
Relative wind speed and direction	Increases ship resistance. An aircraft carrier heads into the wind, the most inefficient course, for flight deck operations. [Ref. 14:p. 133]
Sea State	Creates additional resistance through roll, pitch and yaw. [Ref. 14:p. 133]
Sea Water Temperature	Affects efficiency of heat exchangers in engineering plant. [Ref. 15]
Hull Bottom Fouling	A function of days out of dry dock [Ref. 11:p. A13], can increase resistance up to 20% [Ref. 15].
List, Trim, Draft	Determines the shape of hull in water. [Ref. 15:p. A13]
Plant Configuration	Battle condition, restricted maneuvering, and electrical and steam demand redundancy cause additional demands for power. [Ref. 15]
Turning	Creates additional Propellor Loading. [Ref. 16:p. 285]
Acceleration or Deceleration	Creates transient effects. [Ref. 16:p. 285]
Fuel Type	Two fuels are available for ship's boiler use, F-76 and F-44 Each has a different flash point and efficiency value.
Screws trailing, Locked	Reduces propulsion capability and increases ship drag.
Aircraft Launches	Each aircraft launch results in the loss of fresh water from steam catapult. Fresh water generation requires additional energy.

All conventional aircraft carrier operations require the ship propulsion fuel, F-76. Because the ship's propulsion plant is a deterministic system, one might conclude that fuel usage depends only on the ship's speed required. Thus, by carefully measuring the fuel consumption of a ship across its range of speed capabilities, the fuel consumption for any operation can be calculated by applying this empirical data.

Unfortunately, this conclusion relies on an assumption that a one-to-one correspondence exists between ship's speed, or propulsion plant output and fuel consumption. Any dynamic, deterministic system, such as a ship's engineering plant, requires the specification of initial conditions to predict system behavior over a period of time, until the input conditions change. Though a ship may often be required to proceed at a speed of 15 knots, the input conditions under which the plant must operate to produce an output of 15 knots made good varies considerably, as shown in Table 2.

C ACCELERATED DEGRADATION OF ENGINEERING PLANT PERFORMANCE

The ship's engineering plant gradually degrades in its lifetime of 30+ years. Wear and tear is inevitable, but delayed through a program of overhauls and replacements. This phenomenon is thoroughly anticipated and planned for in the history of any Navy ship by years of documentation and experience. The preponderance of the experience is based on peacetime operating conditions.

The possibility of an accelerated degradation under high tempo extended operations cannot be ignored. However, the last protracted engagement involving an aircraft carrier occurred nearly 50 years ago in the U.S. Navy's

Pacific Campaigns during World War II. The effect that an overused engine--whether it be steam, diesel, or gas--has on fuel consumption during war is given at best a passing comment in literature. Martin Van Creveld states in his book *Supplying War*:

> Moreover the supply of POL was quite insufficient and did not take into account the worn state of the engines. [Ref. 17]

The following table lists a series of potential causes and effects of accelerated degradation of engineering plant performance:

TABLE 3. DEGRADATION OF ENGINEERING PLANT PERFORMANCE

CAUSE	EFFECT
Ship age	Efficiency of engineering plant degrades with time.
Command engineering policy	Inattention or lack of time to conduct Preventative Maintenance System, Heat Stress Management, Valve Maintenance degrades plant performance. [Ref. 5:pp. 6-7; Ref. 15]
Hull Bottom Fouling	Inefficiency increases with time since last hull cleaning. Degree of fouling affected by seawater temperature.
Crew fatigue	Corrective and Preventive Maintenance require time and attention to detail [Ref. 15, Ref. 5:p. 7]. Time at battle stations reduces crew time for sleep and daily equipment maintenance while increasing probability of human error.
Battle Damage	Not necessarily direct damage, but indirect damage by continually exceeding safety margins on equipment to meet constant demands for plant performance.

IV. PROPOSALS FOR IMPROVING FUEL ESTIMATES

A. TIME SAMPLING OF SHIP'S SPEED

The fuel economy cure for any ship is monotonically increasing nonlinear, appearing convex for high speeds. As a result, if the typical distribution of speeds over time is represented by only an average speed, then an underestimate of the estimated fuel consumption for that period will tend to occur. As pointed out earlier, pronounced nonlinearity does not allow the argument that the average speed can be used to well-determine average fuel consumption. The average fuel usage, μ_F, should be a function of at least the average speed, μ_S, the variance of speed, σ_S^2, and possibly even higher moments (e.g. the third moment).

$$\mu_F = f(\mu_S, \sigma_S^2, \ldots)$$

To more accurately model the behavior of the ship over time, and thus to better estimate fuel consumption, a random process of speed versus time should be utilized. Generally, the more variance in the distribution and the higher its mean, the more the need to model with a time-speed process.

Great difficulty may be encountered in determining a distribution of speeds for a carrier involved in flight operations. However, by reducing the engineering operation to three states, which roughly correspond to basic speeds of 15, 20 and 25 knots, the problem may be simplified to provide an illustration. The motivation for such a simplification follows:

An aircraft carrier is capable of a range of speeds from 0 to over 30 knots. However, in accommodating these speeds, the engineering plant goes through a series of discrete states, in each of which it consumes fuel at an approximately constant rate. Orders are sent to the main control of the engineering plant simultaneously in three manners: (RPM) indicator, knots of speed, and engine order telegraph. The engine order telegraph is used along with RPM indicator to notify the engineering plant of the stage or level of operation at which the ship will be demanded to perform. Figure 7 illustrate the scale between knots of speed, RPM, and Engine Order Indicator.

Propellor Revolutions	Speed	Engine Order Indicator
200		
	25 kts	Ahead Flank
150	20	Ahead Full
100	15	Ahead Standard
50	10	Ahead 2/3
	5	Ahead 1/3
0	0	
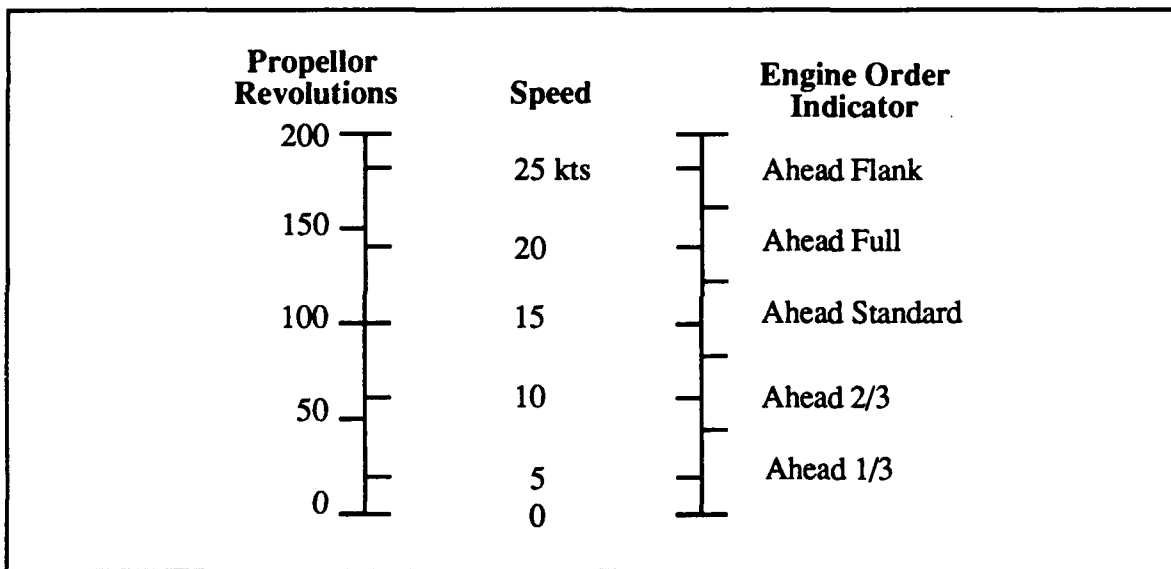
Figure 7. Knots, Propellor Revolution, Engine Order Indicator Scale

The RPM indicator specifies exactly what RPM the bridge desires from the propellor, usually in a range from 0 to over 200. The engine order telegraph divides the RPM scale into five "ahead bell" categories: 1/3, 2/3, standard, full, and flank.

While the purpose of the engine order telegraph is somewhat inconsequential to the ship's bridge team, the telegraph orders convey a broad engine state required of the propulsion plant. In order to understand these states, a brief description of a standard steam propulsion plant is required.

The steam cycle consists of four phases: generation, expansion, condensation, and feed. The flow of steam/condensate through this cycle is harnessed in the propulsion and service generator (electric power producing) turbines. As the RPM is increased from 0 on the ship's propellor, the demand from the propulsion turbine increases. Likewise, the demand for steam flow increases.

Because the range of steam flow must be large to accommodate the range of speeds, auxiliary equipment consisting of various pumps, motors, and fuel burners are staged to accommodate speed increases. The stages are roughly identified by the engine order telegraph. For *standard* speed, only a portion of the equipment must be used. Additional equipment is idle. For *full* order, the additional equipment is brought on line to allow for increase in flow, yet full capacity of all equipment is not required. The final ahead order, *flank*, requires the full capacity of all auxiliary equipment. The auxiliary and main propulsion equipment combine to use steam flow, generated by fuel combustion in the boilers, to propel the ship.

This thesis will consider only the three categories which constitute the overwhelming majority of speeds required in most naval operations. These are *standard, full,* and *flank* ahead bells.

B. DISTRIBUTION OF FUEL CONSUMPTION BY SPEED

For each speed ordered, a distribution of fuel consumption rates may occur. The *Study of Consumption Factors and Requirements Estimates for Ship's Propulsion Fuels* recommends updating fuel curves to include a minimum and maximum in addition to the average fuel use by speed [Ref. 4:Appendix C, p. 24]. To establish a minimum fuel consumption rate for each speed, a curve which fits NWP 11-1 fuel economy data is used. NWP-11 contains the published fuel consumption rates for each speed of all classes of ships [Ref. 3]. Because these data are obtained in accordance with NSTM Chapter 094 specifications [Ref. 11] for fuel economy trials, which state that the data represents the ship *under optimal conditions*, it is assumed that all variations in engineering performance occur *above* these standard rates.

No detailed ship trial data exist which quantifies the fuel characteristics of members of each class of ship under *different conditions of weather*, engineering configuration, and ship age. Such trials are recommended by NSTM Chapter 094 under the description of "Steaming Characteristics," yet are not required [Ref. 11:p. B7]. Thus, any attempt to model the distribution of fuel characteristics for each speed is only an approximation by the author to tentatively aggregate the interaction of factors which determine fuel consumption. In this thesis a distribution of fuel consumption rates with mean μ_F, a value greater than the standard NWP 11-1 rate, and variance σ_F^2 is supposed to determine the percentage increase in fuel consumption for each engineering state which occurs as a result of variance in individual engineering plant performance. The values μ_F and σ_F^2 will be a function of

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the tempo and diversity of operations in which the aircraft carrier is engaged in.

C TIME DEPENDENCE OF LOGNORMAL DISTRIBUTION OF FUEL CONSUMPTION BY SPEED

During peacetime, steady-state steaming the average fuel consumption for each speed would probably be nearly time independent. Under such conditions wear and tear would have predictable effects on the endurance of the fuel capacity of a ship. Fuel consumption may not occur as theoretical fuel curves state, but it could be expected to resemble any data taken in the previous months. Such assumptions may not hold if extended, high tempo operations, such as carrier flight deck operations, are carried out against a capable enemy for two weeks or more.

Using the assumption of lognormal increases in the distribution of fuel consumption characteristics, the mean and standard deviation of the distribution may be slightly increased daily. Increases in these parameters in the simulation are illustrative and not based on empirical data.

This model is presented as an illustration, and is not based on a hard-data analysis, but its implications may suggest the value of such an analysis.

V. SIMULATION OF CV-63 CLASS AIRCRAFT CARRIER FUEL CONSUMPTION

A. MODEL

FORTRAN 77 was used in a program to simulate the behavior of the CV-63 class aircraft carrier. The two Markov Chains shown in Figure 8 were used in the simulation to represent two environments: wartime and peacetime. Combinations of these peacetime and wartime environments comprise each of the three scenarios of the simulation. Each environment has unique Markov chain transition probabilities, but both environments use the same three states. The states, numbered 15, 20, and 25, correspond with medium, high, and very high speeds. Speed changes are modeled by state transitions and are implemented using the random number generator LLRAND II [Ref. 18] to determine a new speed for the ship each hour based on the transition probabilities of figure 8.

Peacetime Environment   Wartime Environment

$\pi_1 = 1/12$ $\pi_2 = 5/6$ $\pi_3 = 1/12$ $\pi_1 = \pi_2 = \pi_3 = 1/3$
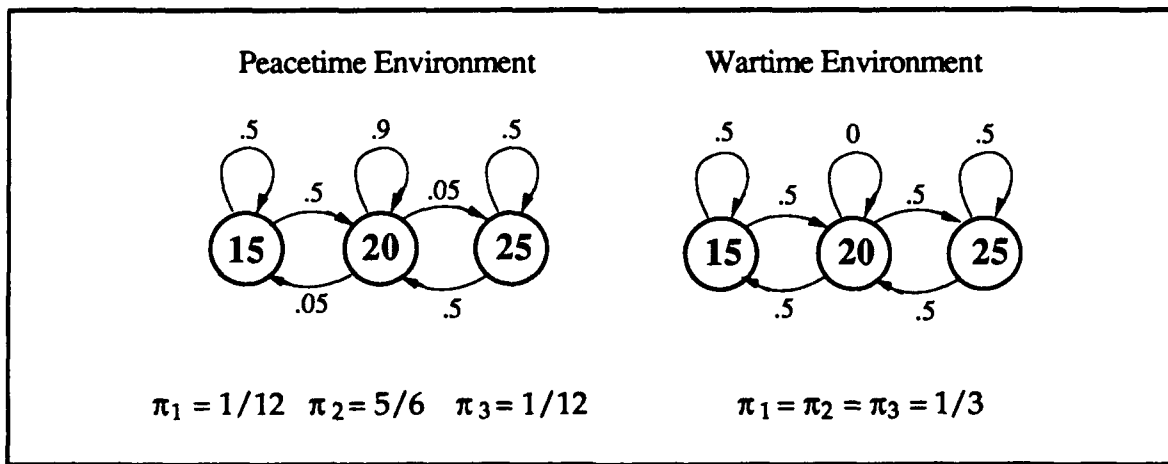
Figure 8. Markov Chain Model

Since a state represents the aircraft carrier's speed for one hour, each state can be further described as the amount of fuel consumed in one hour. A fourth order polynomial fit of the fuel consumption data (Figure 1) was used to determine the relationship between speed and fuel use. Following each hour of simulation time, fuel consumption was calculated using the speed held by the ship during the last hour and was subtracted from the ship's fuel capacity. The simulation was allowed to progress until one million gallons of propulsion fuel had been consumed. This quantity of fuel is roughly half of the ship's fuel capacity and is assumed to be the maximum amount the ship would be allowed to consume before halting its operations to refuel.

Additional conditions were added to each scenario which used a distribution of fuel consumption rates for each speed. The published fuel rate from NWP 11-1 is considered to be conservative and may not reflect variations in engineering plant performance. As a result, the NWP 11-1 fuel rate for each speed determines the minimum of a distribution based on the log-normal distribution. To illustrate, suppose Z is a random variable having a log-normal distribution with

$$E[Z] = 0.10$$

$$Var[Z] = 0.05.$$

Then let Y be the random variable

$$Y = (1 + Z)m$$

where m is the NWP 11-1 fuel rate, and E[Z] is the expected percentage increase in the fuel consumption rate over NWP 11-1 data experienced by the

ship. Let F be the distribution of Y. The mean and variance of this random variable Y would be

$$E[Y] = mE[1 + Z] = m(1.10)$$

$$Var[Y] = m^2 Var[(1 + Z)]$$

$$= m^2 Var[Z]$$

$$= m^2 (0.05)$$

$$St.Dev.[Y] = m\sqrt{0.05}$$

The fuel consumption rates will always be higher than those recorded during operationally restrictive ship trials. The mean μ_F of the log-normal based distribution F was set to a 10 to 30 percent increase (depending on the scenario) from the minimum, or published, fuel usage rate to illustrate a degree of engineering plant degradation discussed in Chapter III. For similar reasons, the variance σ_F^2 of the distribution was selected to be 5 to 15 percent of

the published rate for each speed (again, depending upon the scenario). The final condition added to only the third scenario allows the mean and variance of this log-normal based distribution of fuel consumption rates to slowly increase with time, under wartime conditions.

Three scenarios, each affected separately by two to three conditions, are simulated to determine the length of time required to consume one million gallons of propulsion fuel. The results give insight into the length of time the aircraft carrier has between mandatory refuelings.

A. DESCRIPTION OF SCENARIOS

1. Scenario One: Peacetime, Ocean Transit

The aircraft carrier conducts operations described by the peacetime environment throughout this scenario. Thus, over the long run the ship maintains a relatively constant speed of 20 knots for 83% of the time. Excursions to 25 knots or 15 knots occur only 8.3% of the time, each. The initial conditions for the simulation are determined by the limiting probabilities of the peacetime environment Markov Chain (Figure 8). The endurance capability of the aircraft carrier with respect to propulsion fuel is examined by simulating one thousand times the length of time required to consume one million gallons of F-76 propulsion fuel under three conditions:

- Entering the general average speed of 20 knots into NWP 11-1 fuel consumption data.

- Using the peacetime environment Markov Chain to model speed changes and fuel consumption. Ship's speed each hour determines fuel use per hour by using NWP 11-1 data on fuel economy.

- Enhancing the randomness of the previous condition by using a log-normal based distribution of fuel rates with mean of 110% of NWP 11-1 data and variance of 5% of NWP 11-1 data for each speed. A new fuel rate for each speed is sampled from the respective distribution at the beginning of each simulation replication (one million gallons consumed). These fuel rates are in effect during the entire replication.

This scenarios typifies an open ocean transit where the only concern is timely arrival. Occasionally, some speed changes are required to perform underway replenishments of fuel and stores or short flight operations for training.

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2. Scenario Two: Peacetime, Ocean Transit followed by 24 hour period of Wartime, Flight Deck Operations

Both peacetime and wartime environments constitute the second scenario. The initial conditions for beginning of the simulation are determined by the limiting probabilities of the peacetime environment Markov Chain (Figure 8). First, the fuel consumption for a 24 hour period at wartime levels is simulated. Initial conditions are resampled for the Markov chain using peacetime environment limiting probabilities, and the remainder of the one million gallons fuel is then expended using the peacetime environment Markov Chain.

The purpose of Simulation Two is to approximate a period of open ocean transit immediately followed by a 24 hour period of continuous, flight deck operations (the simulation actually generated the 24 hour wartime fuel consumption before the peacetime fuel consumption period). Speeds of 15, 20, and 25 knots are equally likely in this wartime environment. Insight may be gained on how a brief period of sustained high tempo operations reduces the time until the ship must replenish with fuel again. The time required to burn one million gallons of fuel is again examined under the same three conditions found in scenario one.

- Entering the general average speed of 20 knots into NWP 11-1 fuel consumption data.
- Using the peacetime followed by wartime environment Markov Chain to model speed changes and fuel consumption. Ship's speed each hour determines fuel use per hour by using NWP 11-1 data on fuel economy.
- Enhancing the randomness of the previous condition by using a log-normal based distribution of fuel rates for each speed. The peacetime environment uses a mean of 110% of NWP 11-1 data and variance of 5% of NWP 11-1 data for each speed. The wartime environment uses

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an increased mean of 125% of NWP 11-1 data and variance of 10% of NWP 11-1 data for each speed. A new fuel rate for each speed in each environment is sampled at the beginning of each simulation replication (one million gallons consumed).

3. Scenario Three: Continuous Wartime, Flight Deck Operations

The final scenario tests the endurance of the aircraft carrier under a continuous, wartime environment of 24 hour flight deck operations. The initial states for this scenario are determined by the limiting probabilities of the ocean transit environment. However the remaining simulation time is spent in flight deck operations. This wartime environment Markov Chain has limiting probabilities of 1/3 for each state.

Continuous flight deck operations are required of an aircraft carrier involved in a conflict with a capable enemy. Propulsion fuel endurance becomes a critical measure because it determines the time the ship may conduct offensive and defensive operations before retreating to conduct underway fuel replenishment. In addition to the three conditions of the first two scenarios, a fourth condition of accelerated wear in the engineering plant is added. The four conditions are:

- Entering the general average speed of 20 knots into NWP 11-1 fuel consumption data.

- Using the wartime environment Markov Chain to model speed changes and fuel consumption. Ship's speed each hour determines fuel use per hour by using NWP 11-1 data on fuel economy.

- Enhancing the randomness of the previous condition by using a log-normal based distribution of fuel rates. The wartime environment uses a mean of 125% of NWP 11-1 data and variance of 10% of NWP 11-1 data for each speed. A new fuel rate for each speed is sampled from the respective fuel distribution at the beginning of each simulation replication (one million gallons consumed). These fuel rates are in effect during the entire replication.

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- Increasing the fuel distribution mean by 2% of NWP 11-1 data and the variance by 1% of NWP 11-1 data daily. Thus, the fuel distribution is sampled every 24 hours in each replication.

B. RESULTS OF SCENARIOS

Tables 4,5,and 6 show the results from the three scenarios. Statistics on the distribution of time to consume one million gallons of fuel (endurance time) are listed for the simulation replications.

1. Scenario One

TABLE 4. SCENARIO ONE SIMULATION RESULTS

CONDITION	TIME TO 1 MGAL IN HOURS
Use only average speed to calculate fuel consumption	Average: 194 St. Dev: None
Use Markov Chain for time-sampling	Average: 187.5 St. Dev: 5.1
Using Markov Chain with a fuel distribution (Mu = 1.10, V = .05) giving percentage increases in fuel rate for each speed.	Average: 170.4 St. Dev: 4.9

2. Scenario Two

TABLE 5. SCENARIO TWO SIMULATION RESULTS

CONDITION	TIME TO 1 MGAL IN HOURS
Use only average speed to calculate fuel consumption	Average: 194 St. Dev: None
Use Markov Chain for time-sampling	Average: 158.5 St. Dev: 8.4
Using Markov Chain with a fuel distribution (Mu = 1.10, V = .05) giving percentage increases in fuel rate peacetime and a fuel distribution (Mu = 1.25, V = .10) giving percentage increases in fuel rate wartime	Average: 145.5 St. Dev: 9.6

3. Scenario Three

TABLE 6. SCENARIO THREE SIMULATION RESULTS

CONDITION	TIME TO 1 MGAL IN HOURS
Use only average speed to calculate fuel consumption	Average: 194 St. Dev: None
Use Markov Chain for time-sampling	Average: 170.6 St. Dev: 8.6
Using Markov Chain with a fuel distribution (Mu = 1.25, V = .10) giving percentage increases in fuel rate for each speed.	Average: 136.7 St. Dev: 8.2
Increase fuel distribution Mu by .02 and V by .01 every 24 hours.	Average: 132.4 St. Dev: 10.0

C. COMPARISON OF RESULTS

As each condition was introduced in the simulations, the mean and variance of the fuel consumption rate increased. Consequently the aircraft carrier endurance, or time to consume one million gallons of fuel, decreased in mean and increased in variance. Further, as the scenarios progressed from a steady ocean transit to fast paced flight deck operations, the same phenomena occurred. Yet under all environments and conditions the average speed remained 20 knots. By adding more demanding conditions to each scenario and introducing new scenarios with a higher tempo of operations, both the amount of predicted endurance and the predictability of that endurance decreased.

D. ANALYSIS

Modeling an aircraft carrier's operational variability with a Markov Chain and sampling fuel consumption rates from a log-normal based

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distribution introduced variability in the time required to expend one million gallons of propulsion fuel. The time distributions from the variations of each scenario (Tables 4,5, and 6) suggest a Normal distribution. A cumulative empirical distribution of the time to burn one million gallons plotted against a fitted Normal cumulative distribution is used to evaluate the resemblance of the data to the Normal. Figures 9 through 15 illustrate the results of the evaluation for each change in scenario during the simulation. The Normal fit to the distribution of time improved with the increasing randomness introduced by each scenario change. However, with only three possible speeds, and a relatively narrow distribution of fuel consumption rates for each speed, a normal distribution appears to accurately approximate the distribution of times to consume one million gallons of propulsion fuel, or endurance time. With improvements in the simulation, such as additional speeds and more frequent speed changes, the use of a normal distribution would appear to be a suitable description of the endurance time of the carrier.
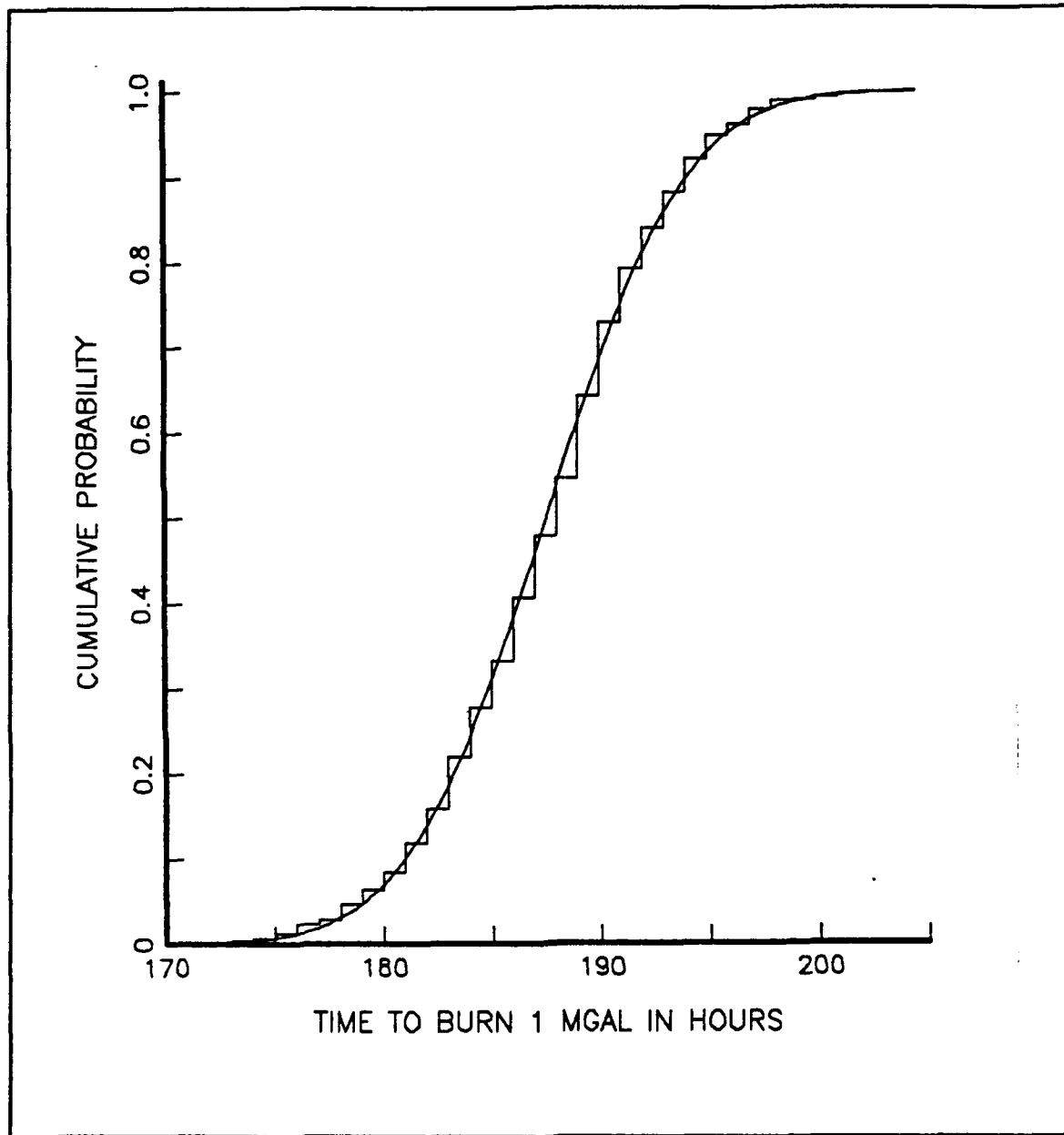
Figure 9.   Cumulative Empirical Distribution of Endurance Time with
Normal Fit: Simulation One using only Markov Chain

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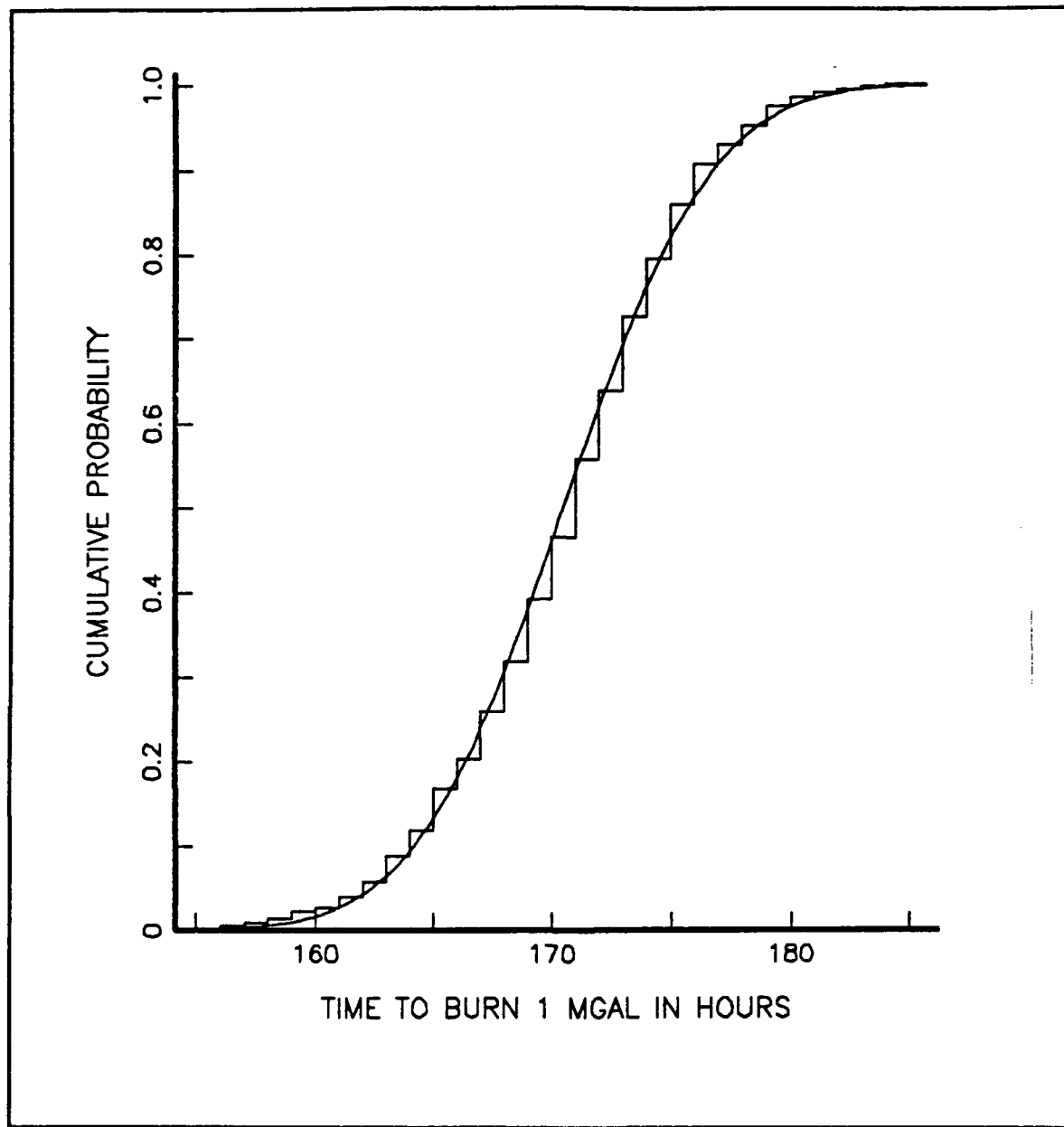
Figure 10.   Cumulative Empirical Distribution of Endurance Time with
Normal Fit: Simulation One using Markov Chain and Sampling from Fuel
Distribution

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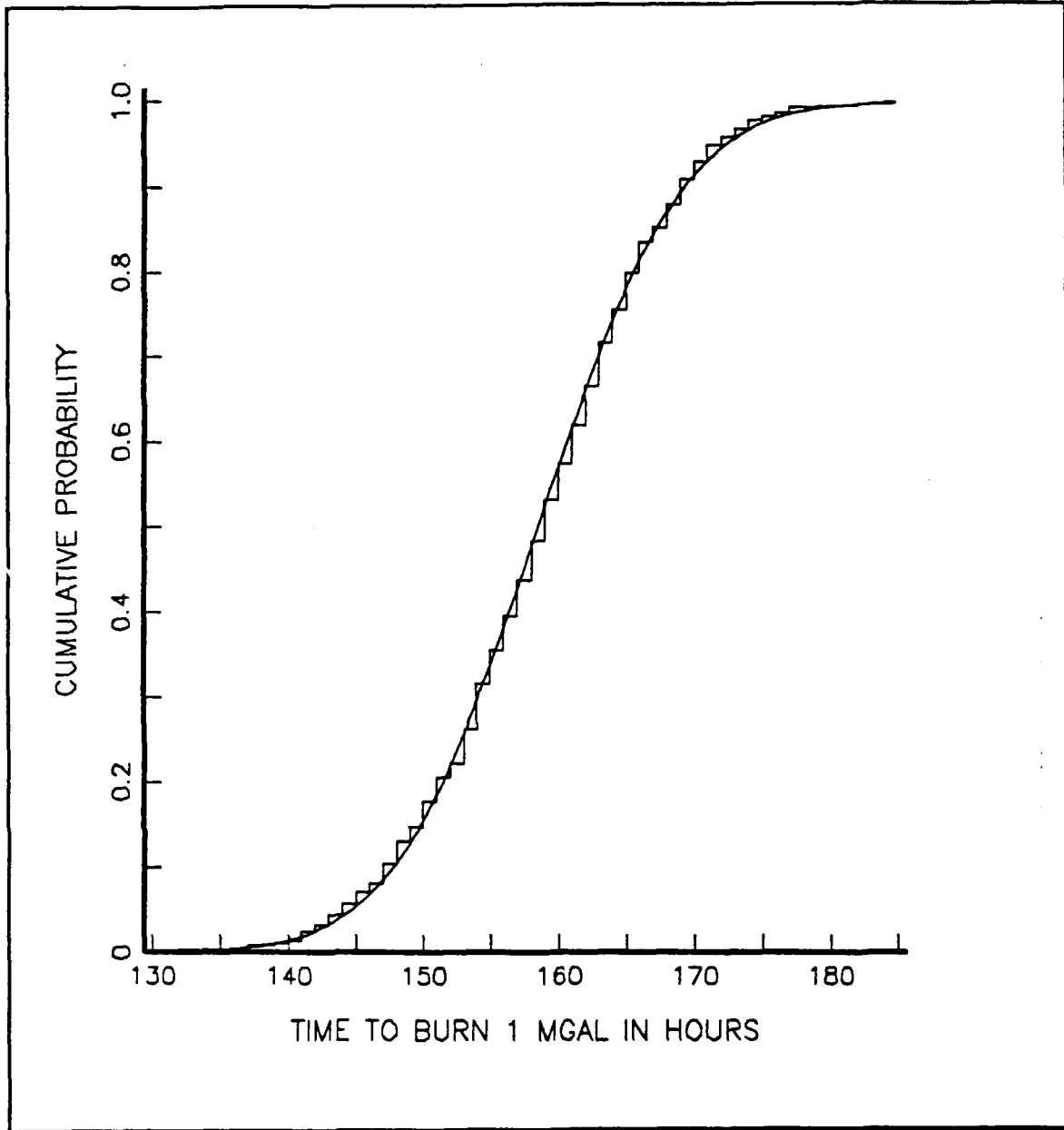
Figure 11. Cumulative Empirical Distribution of Endurance Time with
Normal Fit: Simulation Two using only Markov Chain

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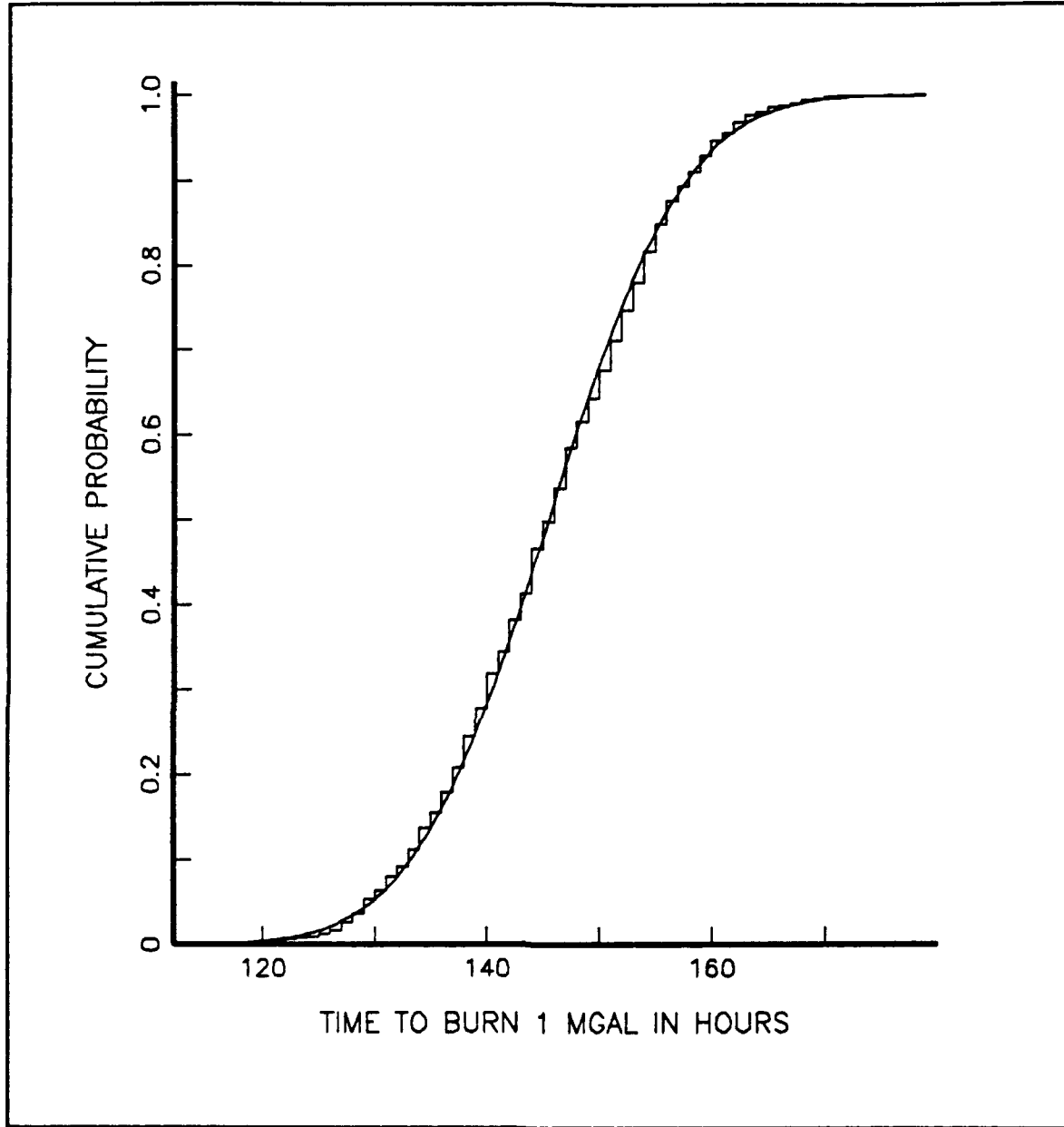
Figure 12.   Cumulative Empirical Distribution of Endurance Time with
Normal Fit: Simulation Two using Markov Chain and Sampling from Fuel
Distribution
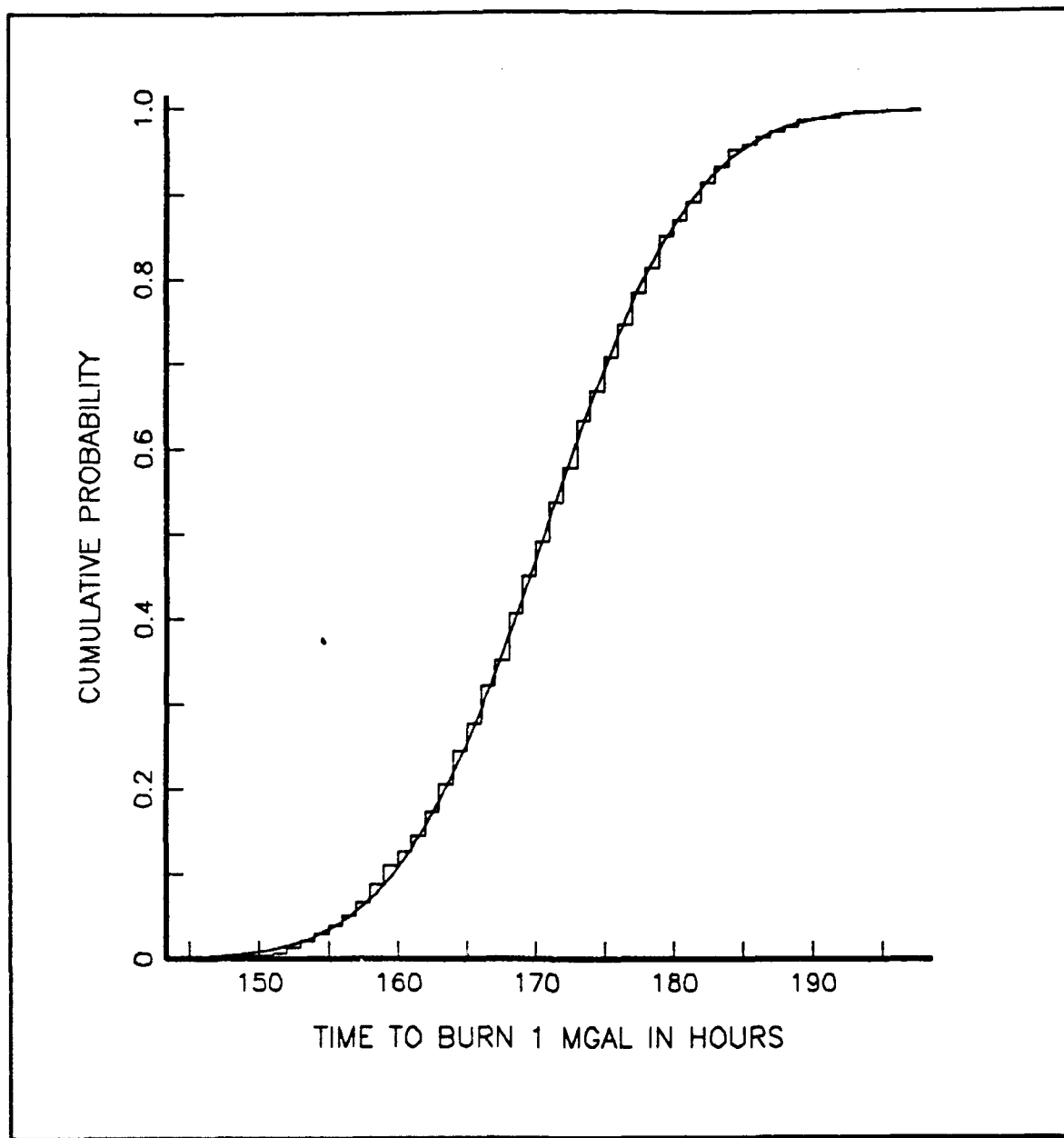
Figure 13. Cumulative Empirical Distribution of Endurance Time with Normal Fit: Simulation Three using only Markov Chain
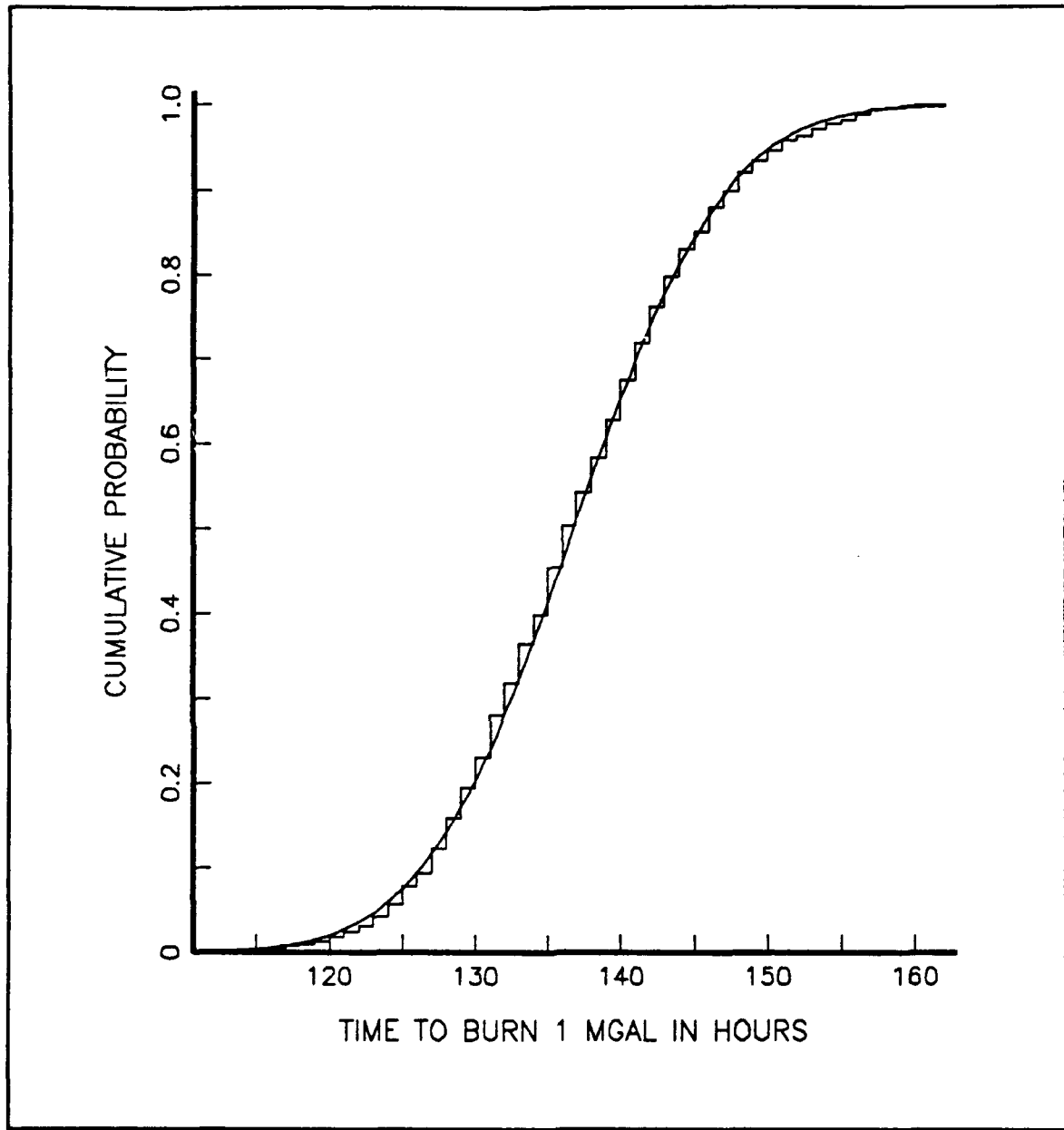
Figure 14. Cumulative Empirical Distribution of Endurance Time with Normal Fit: Simulation Three using Markov Chain and Sampling from Fuel Distribution
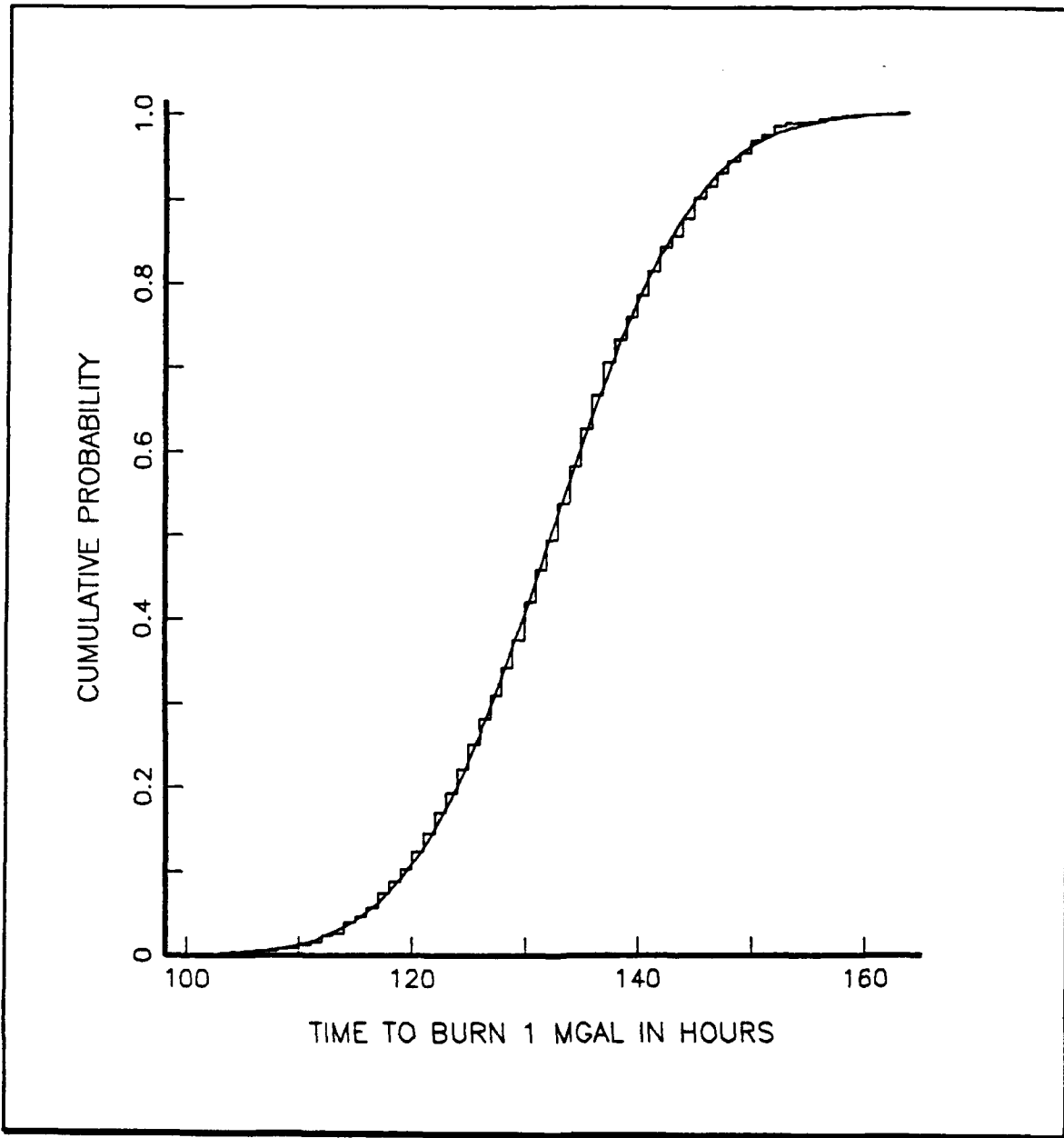
Figure 15. Cumulative Empirical Distribution of Endurance Time with
Normal Fit: Simulation Three using Markov Chain and Sampling from
Fuel Distribution with Increasing Parameters

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VI. CONCLUSIONS

A. MODELING UNPREDICTABILITY IN THE SIMULATION

Variation in operational and performance parameters are a reality in the propulsion plant of any ship. Unfortunately, time and budget constraints prevent adequate trials to determine such effects, even though NSTM Chapter 094 recommends such trials under different conditions of displacement, bottom fouling, wind and sea state[Ref 11, p. B7]. The first time that the resistance of a large ship has been measured to accuracy to determine the effects of ship fouling, hull resistance, and propellor performance was on the civilian tanker ship *Exxon Philadelphia* [Ref 19:p. 98,106].

While accurate measurements are made on newly commissioned ships, rarely can a US Navy aircraft carrier frequently conduct the type of trials needed to accurately determine these variations. Though this thesis only addresses steam propulsion plants on aircraft carriers, similiar phenomena would occur on other steam propulsion ships and gas turbine powered ships. In fact, the lower drive train inertia of gas turbine propelled ships should allow the effects of the seas to have even greater influence on the engines and drive trains [Ref. 16:p. 283].

One straightforward solution to the problem of predicting fuel consumption would be to require the aircraft carrier to report all speed changes throughout the day rather than only a daily fuel consumption report, as is done now. This would generate more data relevant to the performance of the ship while the ship is actually in its operational environment. CAPT

Zwirschitz recommended changing fuel estimates from a daily basis to an hourly basis [Ref 5: p. 10]. Requiring more data is a logical progression towards solving the problem of accuracy. However, requirements for more information may be fundamentally flawed. Centralized logistic coordination by the Army in the Vietnam War required constant, detailed communications from its units to support the accurate statistical models needed for forecasts. The result was a counterproductive burden on the fighting units [Ref. 20: p. 245]. Hence, collecting real-time data from the aircraft carrier on her speed changes and fuel economy to enhance the accuracy of fuel consumption forecasts may not be a viable recommendation, unless the collection process can be reliably automated.

B. IMPLICATIONS OF SIMULATION RESULTS FOR LOGISTICS FORECASTS

The use of computer simulation of aircraft carrier fuel endurance generated some key points on fuel estimate methodology:

- The predicted endurance of an aircraft carrier may decrease in expected value and predictability as the ship is expected to increase operational tempo, even if the average speed remains the same.

- Published fuel economy data for aircraft carriers is based on the operationally sterile environment of engineering trials. Consequently, unpredictabilities in engineering plant and crew under high tempo operations, such as response to enemy action, generate unpredictabilities in fuel consumption rates.

- The variations in fuel consumption rate have direct impact on the operational endurance of the aircraft carrier and should be considered in logistics planning.

- The behavior of fuel consumption in an aircraft carrier during peace should not be the sole basis for wartime prediction levels. War is not predictable environment.

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APPENDIX A. FORTRAN PROGRAM SIMULATIONS

These listings contain the FORTRAN 77 code used to generate each simulation.

A. SCENARIO ONE

1. Markov Chain Only

```
      PROGRAM T1
      REAL DICE1(100000), DICE2(1000), UNINOR(1000), ACTNOR(1000)
      REAL LOGNOR(1000), CUMDAT(1000), TR3DAT(1000), TR4DAT(1000)
      REAL VEL(1000)
      REAL CUMUSE, USE, EY, PERDEV, DEL, MU, CUMHR
      INTEGER I, J, K, V

      CALL EXCMS('FILEDEF 01 DISK SC1B OUTPUT A1')
      CALL SRND(9,DICE1,100000,2,0)
      CALL SRND(10,DICE2,1000,2,0)

      K = 0

      DO 100 I = 1,1000

          IF (DICE2(I) .LT. .0833) THEN
              V = 15
          ELSE
              IF (DICE2(I) .GT. .9167) THEN
                  V = 25
              ELSE
                  V = 20
              ENDIF
          ENDIF


      CUMHR = 0.0
      CUMUSE = 0.0

200   IF (CUMUSE .GT. 1000000.0) THEN
          GOTO 300
      ELSE
          K = K+1

          IF (K .LE. 1000) THEN
              VEL(K) = V
          ENDIF

          IF (K .GT. 100000) THEN
              K = 1
          ENDIF

          USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4

          CUMUSE = CUMUSE + USE
          CUMHR = CUMHR + 1.0
```

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```
        IF (V .EQ. 15) THEN
             IF (DICE1(K) .LT. .50 ) THEN
                   V = 15
             ELSE
                       V = 20
             ENDIF
        ELSE
             IF (V .EQ. 20) THEN
                   IF (DICE1(K) .LT. .05) THEN
                         V = 15
                   ELSE
                         IF (DICE1(K) .GT. .95) THEN
                              V = 25
                         ELSE
                              V = 20
                         ENDIF
                   ENDIF
             ELSE
                   IF (DICE1(K) .GT. .50) THEN
                         V = 25
                   ELSE
                         V = 20
                   ENDIF
             ENDIF
        ENDIF

        ENDIF
        GOTO 200

300     CUMDAT(I) = CUMHR
        WRITE(1,10) CUMHR

100     CONTINUE


*       CALL HISTG (CUMDAT,1000,10)
*       CALL HISTG (VEL,1000,10)

10      FORMAT(F7.1)
        END
```

2. Markov Chain with Distributions of Fuel Consumption Rate

```
        PROGRAM T1
        REAL DICE1(100000), DICE2(1000), UNINOR(1000), ACTNOR(1000)
        REAL LOGNOR(1000), CUMDAT(1000), TR3DAT(1000), TR4DAT(1000)
        REAL VEL(1000)
        REAL CUMUSE, USE, EY, PERDEV, DEL, MU, CUMHR
        INTEGER I, J, K, V

        CALL EXCMS('FILEDEF 01 DISK SC1C OUTPUT A1')
        CALL SNOR(8,UNINOR,1000,2,0)
        CALL SRND(9,DICE1,100000,2,0)
        CALL SRND(10,DICE2,1000,2,0)

        PRINT *,'ENTER E(Y), TO BE ADDED TO 1'
        READ(5,*) EY
        PRINT*,'ENTER % FOR SDEV/EY'
        READ(5,*) PERDEV
        DEL = SQRT(LOG(PERDEV**2+1))
        MU = LOG(EY)-DEL**2/2

        K = 0

        DO 100 I = 1,1000

            IF (DICE2(I) .LT. .0833) THEN
                V = 15
            ELSE
                IF (DICE2(I) .GT. .9167) THEN
                    V = 25
                ELSE
                    V = 20
                ENDIF
            ENDIF

        CUMHR = 0.0
        CUMUSE = 0.0
        ACTNOR(I) = DEL*UNINOR(I)+MU
        LOGNOR(I) = EXP(ACTNOR(I))

200     IF (CUMUSE .GT. 1000000.0) THEN
            GOTO 300
        ELSE
            K = K+1

            IF (K .LE. 1000) THEN
                VEL(K) = V
            ENDIF

            IF (K .GT. 100000) THEN
                K = 1
            ENDIF
        USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4
        USE = USE*(1+LOGNOR(I))
        CUMUSE = CUMUSE + USE
        CUMHR = CUMHR + 1.0
```

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```fortran
          IF (V .EQ. 15) THEN
              IF (DICE1(K) .LT. .50 ) THEN
                  V = 15
              ELSE
                      V = 20
              ENDIF
          ELSE
              IF (V .EQ. 20) THEN
                  IF (DICE1(K) .LT. .05) THEN
                      V = 15
                  ELSE
                      IF (DICE1(K) .GT. .95) THEN
                          V = 25
                      ELSE
                          V = 20
                      ENDIF
                  ENDIF
              ELSE
                  IF (DICE1(K) .GT. .50) THEN
                      V = 25
                  ELSE
                      V = 20
                  ENDIF
              ENDIF
          ENDIF

          ENDIF
          GOTO 200

300       CUMDAT(I) = CUMHR
          WRITE (1,10) CUMHR


100       CONTINUE

10        FORMAT(F7.1)

*         CALL HISTG (CUMDAT,1000,10)
*         CALL HISTG (VEL,1000,10)

          END
```

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B. SCENARIO TWO

1. Markov Chain Only

```
PROGRAM T1
REAL DICE1(100000), DICE2(1000), UNINOR(1000), ACTNOR(1000)
REAL LOGNOR(1000), CUMDAT(1000), TR3DAT(1000), TR4DAT(1000)
REAL VEL(1000)
REAL CUMUSE, USE, EY, PERDEV, DEL, MU, CUMHR, HOLD
INTEGER I, J, K, L, V

CALL EXCMS('FILEDEF 01 DISK SC2B OUTPUT A1')
CALL SRND(9,DICE1,100000,2,0)
CALL SRND(10,DICE2,1000,2,0)

K = 0

DO 100 I = 1,1000

     IF (DICE2(I) .LT. .0833) THEN
          V = 15
     ELSE
          IF (DICE2(I) .GT. .9167) THEN
               V = 25
          ELSE
               V = 20
          ENDIF
     ENDIF

CUMHR = 0.0
CUMUSE = 0.0

DO 400 L = 1,24
     K = K + 1

     USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4

     CUMUSE = CUMUSE + USE
     CUMHR = CUMHR + 1.0

IF (V .EQ. 15) THEN
     IF (DICE1(K) .LT. .50 ) THEN
          V = 15
     ELSE
               V = 20
     ENDIF
ELSE
     IF (V .EQ. 20) THEN
          IF (DICE1(K) .LT. .50) THEN
               V = 15
          ELSE
               V = 25
          ENDIF
     ELSE
          IF (DICE1(K) .GT. .50) THEN
               V = 25
```

```
                    ELSE
                          V = 20
                    ENDIF
              ENDIF
        ENDIF

400     CONTINUE
        HOLD = CUMUSE

200     IF (CUMUSE .GT. (1000000.0-HOLD)) THEN
              GOTO 300
        ELSE
              K = K+1

              IF (K .GT. 100000) THEN
                    K = 1
              ENDIF

              USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4

              CUMUSE = CUMUSE + USE
              CUMHR = CUMHR + 1.0

        IF (V .EQ. 15) THEN
              IF (DICE1(K) .LT. .50 ) THEN
                    V = 15
              ELSE
                          V = 20
              ENDIF
        ELSE
              IF (V .EQ. 20) THEN
                    IF (DICE1(K) .LT. .05) THEN
                          V = 15
                    ELSE
                          IF (DICE1(K) .GT. .95) THEN
                                V = 25
                          ELSE
                                V = 20
                          ENDIF
                    ENDIF
              ELSE
                    IF (DICE1(K) .GT. .50) THEN
                          V = 25
                    ELSE
                          V = 20
                    ENDIF
              ENDIF
        ENDIF

        ENDIF
        GOTO 200

300     CUMDAT(I) = CUMHR

        WRITE(1,10) CUMHR
100     CONTINUE

*       CALL HISTG (CUMDAT,1000,10)

10      FORMAT(F7.1)
        END
```

2. Markov Chain with Distributions of Fuel Consumption Rate

```
PROGRAM T1
REAL DICE1(100000), DICE2(1000), UNINOR(1000), ACTNOR(1000)
REAL LOGNOR(1000), CUMDAT(1000), TR3DAT(1000), TR4DAT(1000)
REAL VEL(1000)
REAL CUMUSE, USE, EY, PERDEV, DEL, MU, CUMHR, HOLD
INTEGER I, J, K, L, V

CALL EXCMS('FILEDEF 01 DISK SC2C OUTPUT A1')
CALL SNOR(8,UNINOR,1000,2,0)
CALL SRND(9,DICE1,100000,2,0)
CALL SRND(10,DICE2,1000,2,0)

K = 0

DO 100 I = 1,1000
    IF (DICE2(I) .LT. .0833) THEN
        V = 15
    ELSE
        IF (DICE2(I) .GT. .9167) THEN
            V = 25
        ELSE
            V = 20
        ENDIF
    ENDIF

EY = .25
PERDEV = .10
DEL = SQRT(LOG(PERDEV**2+1))
MU = LOG(EY)-DEL**2/2
ACTNOR(I) = DEL*UNINOR(I)+MU
LOGNOR(I) = EXP(ACTNOR(
CUMHR = 0.0
CUMUSE = 0.0
DO 400 L = 1,24
    K = K + 1
    USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4
    USE = USE*(1+LOGNOR(I))
    CUMUSE = CUMUSE + USE
    CUMHR = CUMHR + 1.0
IF (V .EQ. 15) THEN
    IF (DICE1(K) .LT. .50 ) THEN
        V = 15
    ELSE
        V = 20
    ENDIF
ELSE
    IF (V .EQ. 20) THEN
        IF (DICE1(K) .LT. .50) THEN
            V = 15
        ELSE
            V = 25
        ENDIF
    ELSE
        IF (DICE1(K) .GT. .50) THEN
            V = 25
        ELSE
```

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```fortran
                              V = 20
                    ENDIF
               ENDIF
          ENDIF
400       CONTINUE
          HOLD = CUMUSE
          EY = .10
          PERDEV = .05
          DEL = SQRT(LOG(PERDEV**2+1))
          MU = LOG(EY)-DEL**2/2
          ACTNOR(I) = DEL*UNINOR(I)+MU
          LOGNOR(I) = EXP(ACTNOR(I))

200       IF (CUMUSE .GT. (1000000.0-HOLD)) THEN
               GOTO 300
          ELSE
               K = K+1


               IF (K .GT. 100000) THEN
                    K = 1
               ENDIF
               USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4
               CUMUSE = CUMUSE + USE
               CUMHR = CUMHR + 1.0

          IF (V .EQ. 15) THEN
               IF (DICE1(K) .LT. .50 ) THEN
                    V = 15
               ELSE
                         V = 20
               ENDIF
          ELSE
               IF (V .EQ. 20) THEN
                    IF (DICE1(K) .LT. .05) THEN
                         V = 15
                    ELSE
                         IF (DICE1(K) .GT. .95) THEN
                              V = 25
                         ELSE
                              V = 20
                         ENDIF
                    ENDIF
               ELSE
                    IF (DICE1(K) .GT. .50) THEN
                         V = 25
                    ELSE
                         V = 20
                    ENDIF
               ENDIF
          ENDIF

          ENDIF
          GOTO 200

300       CUMDAT(I) = CUMHR
          WRITE(1,10) CUMHR

100       CONTINUE

10        FORMAT(F7.1)

          END
```

C. SCENARIO THREE

1. Markov Chain Only

```
PROGRAM T1
REAL DICE1(100000), DICE2(1000), UNINOR(1000), ACTNOR(1000)
REAL LOGNOR(1000), CUMDAT(1000), TR3DAT(1000), TR4DAT(1000)
REAL VEL(5000)
REAL CUMUSE, USE, EY, PERDEV, DEL, MU, CUMHR
INTEGER I, J, K, V

CALL EXCMS('FILEDEF 01 DISK SC3B OUTPUT A1')
CALL SRND(9,DICE1,100000,2,0)
CALL SRND(10,DICE2,1000,2,0)

K = 0

DO 100 I = 1,1000

        IF (DICE2(I) .LT. .0833) THEN
            V = 15
        ELSE
            IF (DICE2(I) .GT. .9167) THEN
                V = 25
            ELSE
                V = 20
            ENDIF
        ENDIF

CUMHR = 0.0
CUMUSE = 0.0

200     IF (CUMUSE .GT. 1000000.0) THEN
            GOTO 300
        ELSE
            K = K+1

            IF (K .LE. 5000) THEN
                VEL(K) = V
            ENDIF

            IF (K .GT. 100000) THEN
                K = 1
            ENDIF

            USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4

            CUMUSE = CUMUSE + USE
            CUMHR = CUMHR + 1.0

IF (V .EQ. 15) THEN
        IF (DICE1(K) .LT. .50 ) THEN
            V = 15
        ELSE
                V = 20
        ENDIF
```

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```
        ELSE
            IF (V .EQ. 20) THEN
                IF (DICE1(K) .LT. .50) THEN
                    V = 15
                ELSE
                    V = 25
                ENDIF
            ELSE
                IF (DICE1(K) .GT. .50) THEN
                    V = 25
                ELSE
                    V = 20
                ENDIF
            ENDIF
        ENDIF

        ENDIF
        GOTO 200

300     CUMDAT(I) = CUMHR
        WRITE(1,10) CUMHR

100     CONTINUE

*       CALL HISTG (CUMDAT,1000,10)
*       CALL HISTG (VEL,5000,10)

10      FORMAT(F7.1)
        END
```

2. Markov Chain with Distributions of Fuel Consumption Rate

```
PROGRAM T1
REAL DICE1(100000), DICE2(1000), UNINOR(1000), ACTNOR(1000)
REAL LOGNOR(1000), CUMDAT(1000), TR3DAT(1000), TR4DAT(1000)
REAL VEL(1000)
REAL CUMUSE, USE, EY, PERDEV, DEL, MU, CUMHR
INTEGER I, J, K, V

CALL EXCMS('FILEDEF 01 DISK SC3C OUTPUT A1')

CALL SNOR(8,UNINOR,1000,2,0)
CALL SRND(9,DICE1,100000,2,0)
CALL SRND(10,DICE2,1000,2,0)

EY = .25
PERDEV = .10
DEL = SQRT(LOG(PERDEV**2+1))
MU = LOG(EY)-DEL**2/2

K = 0

DO 100 I = 1,1000

      IF (DICE2(I) .LT. .0833) THEN
            V = 15
      ELSE
            IF (DICE2(I) .GT. .9167) THEN
                  V = 25
            ELSE
                  V = 20
            ENDIF
      ENDIF

CUMHR = 0.0
CUMUSE = 0.0
ACTNOR(I) = DEL*UNINOR(I)+MU
LOGNOR(I) = EXP(ACTNOR(I))

200   IF (CUMUSE .GT. 1000000.0) THEN
            GOTO 300
      ELSE
            K = K+1

      IF (K .LE. 1000) THEN
            VEL(K) = V
      ENDIF

            IF (K .GT. 100000) THEN
                  K = 1
            ENDIF

      USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4
      USE = USE*(1+LOGNOR(I))
```

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```fortran
                CUMUSE = CUMUSE + USE
                CUMHR = CUMHR + 1.0


        IF (V .EQ. 15) THEN
            IF (DICE1(K) .LT. .50 ) THEN
                V = 15
            ELSE
                    V = 20
            ENDIF
        ELSE
            IF (V .EQ. 20) THEN
                IF (DICE1(K) .LT. .50) THEN
                        V = 15
                ELSE
                    V = 25
                ENDIF
            ELSE
                IF (DICE1(K) .GT. .50) THEN
                        V = 25
                ELSE
                    V = 20
                ENDIF
            ENDIF
        ENDIF

        ENDIF
        GOTO 200

300     CUMDAT(I) = CUMHR
        WRITE(1,10) CUMHR

100     CONTINUE

*       CALL HISTG (CUMDAT,1000,10)
*       CALL HISTG (VEL,1000,10)
10      FORMAT(F7.1)

        END
```

3. Markov Chain with Distributions of Fuel Consumption Rate , Mean and Variance Increasing with Time

```
PROGRAM T1
REAL DICE1(100000), DICE2(1000), UNINOR(1000), ACTNOR(1000)
REAL LOGNOR(1000), CUMDAT(1000), TR3DAT(1000), TR4DAT(1000)
REAL VEL(1000)
REAL CUMUSE, USE, EY, PERDEV, DEL, MU, CUMHR
INTEGER I, J, K, L, V

CALL EXCMS('FILEDEF 01 DISK SC3D OUTPUT A1')

CALL SNOR(8,UNINOR,1000,2,0)
CALL SRND(9,DICE1,100000,2,0)
CALL SRND(10,DICE2,1000,2,0)

K = 0

DO 100 I = 1,1000

      IF (DICE2(I) .LT. .0833) THEN
            V = 15
      ELSE
          IF (DICE2(I) .GT. .9167) THEN
                V = 25
          ELSE
                V = 20
          ENDIF
      ENDIF

EY = .23
PERDEV = .19
CUMHR = 0.0
CUMUSE = 0.0

200   EY = EY + .02
PERDEV = PERDEV + .01
DEL = SQRT(LOG(PERDEV**2+1))
MU = LOG(EY)-DEL**2/2
ACTNOR(I) = DEL*UNINOR(I)+MU
LOGNOR(I) = EXP(ACTNOR(I))

DO 400 L = 1,24

      IF (CUMUSE .GT. 1000000.0) THEN
            GOTO 300
      ELSE
          K = K+1

          IF (K .LE. 1000) THEN
                VEL(K) = V
          ENDIF

          IF (K .GT. 100000) THEN
                K = 1
          ENDIF

          USE = 1885.9-285.42*V+58.04*V**2-3.262*V**3+0.07423*V**4
```

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```
                        USE = USE*(1+LOGNOR(I))
                        CUMUSE = CUMUSE + USE
                        CUMHR = CUMHR + 1.0

                        IF (V .EQ. 15) THEN
                            IF (DICE1(K) .LT. .50 ) THEN
                                V = 15
                            ELSE
                                V = 20
                            ENDIF
                        ELSE
                            IF (V .EQ. 20) THEN
                                IF (DICE1(K) .LT. .50) THEN
                                    V = 15
                                ELSE
                                    V = 25
                                ENDIF
                            ELSE
                                IF (DICE1(K) .GT. .50) THEN
                                    V = 25
                                ELSE
                                    V = 20
                                ENDIF
                            ENDIF
                        ENDIF

                ENDIF

400     CONTINUE

        GOTO 200

300     CUMDAT(I) = CUMHR
        WRITE(1,10) CUMHR

100     CONTINUE

*       CALL HISTG (CUMDAT,1000,10)
*       CALL HISTG (VEL,1000,10)
10      FORMAT(F7.1)

        END
```

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REFERENCES

1. Coralski, R. and Freeburg, R. W., *Oil and War*, William Morrow and Company, Inc., New York, 1987.

2. Prangue, G. W., *At Dawn We Slept*, Penguin Books, 1981.

3. Naval Warfare Publication 11-1 (Rev. B), *Characteristics and Capabilities of US Navy Combatant Ships*, 1983.

4. Chief of Naval Operations, *An Analysis of Navy Logistic Planning Factors*, Phase II. v. 1 and 2, by B.A. Gruber, 30 November 1979.

5. Zwirschitz, G. W., *Atlantic Fleet Surface Force Fuel Management.*, Paper, Professional Military Comptroller School, 1986.

6. Chief of Naval Operations, *Study of Consumption Factors and Requirements Estimates for Ship's Propulsion Fuels*, Final Report, 19 April 1966.

7. Hereford, L., and Spiegel, R., *Battle Force Operation Replenishment Model--BFORM Functional Description and User's Manual*, Johns Hopkins University Applies Physics Laboratory, March 1988.

8. Branting, D. L., *User's Guide for the Replenishment-At-Sea Model (RASM)*, Center for Naval Analyses, December 1986.

9. Vondersmith, C. and Miller, E., *Resupply Sealift Requirements Generator User's Manual*, David Taylor Research Center, June 1988.

10. Harris, S., *Comparison of Three Combat Logistics Force Models*, Master's Thesis, Naval Postgraduate School, Monterey, CA, March 1989.

11. *Naval Ship's Technical Manual*, Chapter 094--Trials (Rev. 1), 1978

12. Center for Naval Analysis, *Lessons Learned in Exercises: Logistics*, S. D. Kleinman, August 1987, 12 p.

13. Feller, *An Introduction to Probability Theory*, 2nd ed., v. 2, Wiley, 1971.

14. Strom-Tejsen, J., Yeh, H., and Moran, D. D., "Added Resistance in Waves," *Society of Naval and Mechanical Engineers Transactions,* v. 81, 1973, p. 109-143. 1973.

15. Telephone Conversation between CDR Isaiah J. Jones, Naval Educaion and Training Center, Fleet Training Group, San Diego, and the author, 26 January 1990.

16. Rubis, C. J. and Harper, T. R., "Governing Ships Propulsion Gas Turbine Engines," *Society of Naval and Mechanical Engineers Transactions,* v. 94, p. 283-308, 1986.

17. Van Creveld, M., *Supplying War,* Cambridge University Press, Cambridge, 1977.

18. Lewis, P.A.W., and Uribe, L., *"The New Naval Postgraduate School Random Number Package LLRANDOM II ",* Naval Postgraduate School Report NPS55-81-005, Naval Postgraduate School, February 1981.

19. Abkowitz, M. and Liu, G., "Measurement of Ship Resistance, Powering, and Maneuvering Coefficients from Simple Trials during a Regular Voyage," *Society of Naval and Mechanical Engineers Transactions,* v. 96, p. 97-128, 1988.

20. Van Creveld, M., *Command in War,* Harvard University Press, Cambridge, 1985.

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